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# EVAPORATION AND EVAPOTRANSPIRATION PROCESSES

Edited by

F.J. Eley

ATMOSPHERIC ENVIRONMENT SERVICE

NATIONAL HYDROLOGY RESEARCH CENTRE
SASKATOON, SASKATCHEWAN

1988

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PROCEEDINGS OF THE WORKSHOP ON

# EVAPORATION AND EVAPOTRANSPIRATION PROCESSES

MAY 20 AND 21, 1987

NATIONAL HYDROLOGY RESEARCH CENTRE

SASKATOON, SASKATCHEWAN

Edited by
F.J. Eley
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Saskatoon, Saskatchewan

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## ABSTRACT

A Workshop on evaporation and evapotranspiration processes was hosted by the Hydrometeorology Research Division of the Canadian Climate Centre at the National Hydrology Research Centre in Saskatoon on May 20 and 21, 1987. Over 55 people from both research and applications areas participated in the discussions on the state of knowledge of evaporation processes and made recommendations on areas in which additional research is required. Presentations were also given on upcoming international research efforts related to modelling and measuring of evaporation and evapotranspiration.

The discussions covered three broad subject areas: measurement, remote sensing and modelling. Measurement topics covered included: Class "A" evaporation pans, small atmometers; and the groundwater system as a large-scale lysimeter. Remote sensing topics included experience with airborne eddy correlation equipment and the potential for inference of evaporation from spaceborne sensors. A number of evaporation estimation models were discussed, in most cases in the context of their best applications, such as reservoir management, irrigation scheduling or general climate modelling.

The research recommendations resulting from the discussions in the workshop dealt with both the measurement and modelling aspects of evaporation and evapotranspiration. There is a need to establish a procedure that can be used to publish official estimates of evaporation in place of the present official record of Class "A" pan observations. Further research is needed to fully utilize remote sensing in estimating evapotranspiration. Further development of practical evapotranspiration models is recommended, with emphasis on the refinement of proven models.

## RÉSUMÉ

A Saskatoon, à la Division de la recherche hydrométéorologique (Hydrometeorology Research Division) du Centre climatologique canadien, au Centre national de la recherche hydrologique (National Hydrology Research Centre), s'est déroulé les 20 et 21 mai 1987 un atelier sur les processus d'évaporation et d'évapotranspiration. Plus de 55 personnes, qui se consacraient aux domaines de la recherche ou des applications, ont participé aux discussions concernant les connaissances actuelles sur les processus d'évaporation, et ont formulé des recommandations à propos des secteurs exigeant de la recherche supplémentaire. Des exposés ont aussi été faits sur les efforts internationaux de recherche qui s'appliqueront à la modélisation et à la mesure de l'évaporation et de l'évapotranspiration.

Les discussions ont porté sur trois grands thèmes : la mesure, la télédètection et la modélisation. Les sujets abordés, à propos des méthodes de mesure. étaient : l'usage des bacs à évaporation de classe "A", de petits atmomètres; et l'emploi du rèseau hydrologique souterrain, considéré comme un lysimètre de grande envergure. Dans le domaine de la télédètection, on a traité de l'expérience acquise avec le matériel de corrélation de tourbillons de turbulence atmosphérique, et des possibilités d'évaluation de l'évaporation à partir de capteurs satioportès. On a étudié un certain nombre de modèles d'estimation de l'évaporation, le plus souvent dans le contexte de leurs meilleures applications, comme la régulation des réservoirs, la programmation de l'irrigation ou la modélisation générale du climat.

Les recommandations en matière de recherche, formulées à la suite de l'atelier, concernaient à la fois les détails de la mesure de la modélisation des processus d'évaporation et

d'évapotranspiration. Il serait nécessaire d'établir une méthode qui permette de publier les estimations officielles sur l'évaporation, à la place relevés officiels actuels basés sur les observations faites avec les bacs de classe "A". Il faudrait faire plus de recherche, pour tirer pleinement profit de la télédètection dans le but d'évaluer l'évapotranspiration. On recommande de poursuivre la mise au point des modèles pratiques d'évapotranspiration, en mettant l'accent sur le perfectionnement des modèles éprouvés.

## PREFACE

The newly formed Hydrometeorological Research Division hosted its first workshop in May 1987. The following report summarizes the proceedings of this two-day event. The theme of the workshop, Evaporation and Evapotranspiration, was decided on after extensive consultations with water resource agencies in the Prairie provinces. Evaporation is a particularly important component of the water balance in southern Alberta and Saskatchewan. Although evaporation alone was initially considered for the conference theme, it quickly became evident that there were many research interests and operational demands in the area of evapotranspiration which should be addressed in the same forum. Accordingly, the scope of the workshop was broadened to include evapotranspiration. This meant that a larger number of presentations than had originally been envisioned were incorporated into the program.

The workshop was structured to achieve the following objectives:

1) Through presentations and discussion groups, review the state of existing knowledge on evaporation and evapotranspiration.
2) Through discussion groups, identify the need for research activities in the areas of evaporation and evapotranspiration appropriate for the Hydrometeorological Research Division and for other research groups.
3) Through presentations and discussions, familiarize participants with opportunities for involvement in upcoming international projects and assist in the identification of potential Canadian projects and activities which could support the WMO study on the modelling of evapotranspiration.

Before, during and after the workshop a number of individuals expressed an interest in obtaining copies of the workshop proceedings. In order to accommodate these requests, Mr. Joe Eley prepared this summary of the proceedings. We are thankful to the authors who contributed to the program and provided us with their extended abstracts.

The workshop was intended to be a first step in a continuing dialogue between the Hydrometeorlogical Research Division and the user community. Since the newly formed Division had little expertise to offer, it was extremely grateful to other agencies such as the Saskatchewan Research Council, the National Hyrodology Research Institute and other components of the Canadian Climate Centre for their contributions at the workshop. Thanks to the active participation of both the research and the operational communities in this workshop, its results will undoubtedly prove very useful in drawing up the Division's research strategy in area of prairie hydrometeorology.

It should be recognized that this report does not mark the end of this exercise, but rather a beginning. I am very interested in having discussions with any researcher or user who would like to undertake further research, or have it undertaken, as a result of something that they heard at the workshop or have read in this report. Accordingly you are encouraged to read and discuss this report and to contact the undersigned if you feel we may have areas of common interest.

R.G. Lawford
Chief, Hydrometeorological
Research Division

## INTRODUCTION

This Proceedings is a collection of "extended abstracts" of the papers presented at the Workshop, plus edited discussions and edited transcripts of a summary of the workshop. The intent of extended abstracts is to give the author more space to expand on his ideas without the formality or considerable effort of writing up a complete text.

We thank all the authors for their patience in putting up with such a vague definition of the desired inputs, and for waiting so long for the appearance of the proceedings.

I have presented an edit of the full transcript of John Maybank's able wrap-up of the whole workshop, and of the presentations and panel discussions on research opportunities. I have tried to cover all the relevant points that were recorded from the discussions in plenary sessions.

I have written an Executive Summary to pass on to those who were not participants the main points that were discussed in the course of this workshop. The emphasis is on potential research that will have applications in water resources management.

F.J. Eley
October 1, 1987

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## EXECUTIVE SUMMARY

### INTRODUCTION

The Workshop was a meeting of some 60 research and applications scientists, students and managers who came from six provinces and the N.W.T. They represented water resource management, hydro power, agriculture, water pollution control and hydrology research organizations. The importance of evaporation in the practical world of water use was shown throughout the discsussion. As a few examples: Saskatchewan's evaporation everywhere exceeds rainfall; the evaporation from Lake Diefenbaker on a hot summer's day is double the minimum flow of the South Saskatchewan River guaranteed through the City of Saskatoon; the probable error in estimating evaporation from Lake Diefenbaker represents enough water to produce annually $500,000 of electricity at the power-plant bulk rates.

The principal deliberations of the Workshop involved the state of the art and science of estimating evaporation and evapotranspiration for either operations support or long-range planning. Applications discussed ranged from agriculture and hydro power production to river flow apportionment and tailings pond management. Most current forms of measurement were discussed, from evaporation pans to inference from satellite remote sensing. Several presentations reviewed the state of application of remote sensing to evaporation measurement.

The participants produced a long list of research needs with various levels of priority. The principal needs are for field testing of models on a large scale, sensitivity studies to assist in the rational selection of models, and further development of the application of remote sensing to areal evaporation measurement. Several other areas of research needs are listed in the concluding page of this Summary.

### APPLICATIONS

There are many applications of the measurement and estimation of evaporation. Agriculture is one of the most important. Evapotranspiration estimates are used to estimate crop production in support of the general tracking of the farm economy and some forms of crop insurance. Estimates of evapotranspiration are essential to rational irrigation scheduling and to many forms of crop research.

Evaporation estimates are required in flood forecasting for both soil condition models and to estimate losses from open water in the system. Evaporation estimates are required by reservoir operation models. The reservoir inputs and outputs must be well estimated in order to minimize water losses while meeting the diverse needs of hydro power production, flood hazard reduction and water flow to irrigation projects and river recreation.

Good long-term records and forecasts of evaporation are needed to study long-term climate change and its effect. Some models may allow us to detect errors in long-term records, or to detect the effects of land-use change or large-scale water transfers accompanied by a climate change.

An important application in the Prairie Provinces is proper estimation of the consumption of river flow in each province. The flow of rivers across interprovincial and international boundaries is apportioned according to official agreements and evaporation from man-made works (reservoirs) account for a considerable portion of the water used.

The management of tailings ponds from mineral processing requires accurate estimates of evaporation of both uncontaminated water from the surrounding watershed, and from the very concentrated solution in the tailings pond itself. If precipitation on the pond and inflow from the surrounding watershed exceed evaporation, decant of the pond must be arranged safely.

A fire danger index system makes estimates of the dryness of various fuel components, from fine lichens to tree stems to the soil moisture on which they feed. In order to adequately estimate moisture status, accurate estimates of evapotranspiration are needed.

## MEASUREMENT AND ESTIMATION

The Class A Evaporation Pan is the standard instrument for measuring evaporation from lakes. Evaporation from the Class A Pan must be adjusted because it does not represent directly the evaporation from the surface of any lake more than its own size. Many attempts have been made to compensate for these differences.

Small-scale atmometers have been found to represent evaporation from crops just as well as Class A Pans, and with much smaller equipment and water supplies to manage, thus reducing operations costs.

The only fundamental measure of actual evapotranspiration from a whole field of crop is the measurement of the upward moisture flux. Recently, the eddy correlation technique has been expanded from point to linear samples by flying a transect with airborne instruments. Eddy correlation is very difficult to accomplish on routine basis, and is only used in research work. The Bowen Ratio technique of measuring the moisture flux is more likely to be used operationally. Campbell Scientific Corporation presented the state of development of its operational equipment to the Workshop.

The concept of using the variation of groundwater levels in a large aquifer as a giant lysimeter to measure annual soil moisture cycles was presented. The water flow into and out of the groundwater system can be accounted for, except for the component which is caused by the annual cycle of soil moisture, the build-up due to snow and rain, and the decay due to evaporation and run-off. Full treatment of this residual could lead to a better understanding of soil moisture variations.

Since evaporation and evapotranspiration are impossible to directly measure in most practical applications, techniques for their estimation are vital. Several techniques in common use were discussed in the Workshop. The problems of application of these models and of selecting the model with the best estimate for the situation, were the main topics of discussion. Models are often calibrated for one particular geographic area and not fully tested in another area before being applied to make important estimates of past or future evaporation.

The Meyer Formula, used by the Prairie Provinces Water Board and other agencies to estimate losses from lakes, is a semi-empirical relationship which may require more calibration to produce "true" values of evaporation in Saskatchewan. It was developed in the U.S. Midwest, and considerable experience has been developed in its application, It is thus well-established as a guide to reservoir operation on the Prairies. However, operational personnel continue to express concern because it has not been tested and calibrated specifically for the Canadian Prairies.

Morton's Complementary Relationship Areal Evapotranspiration (CRAE) Model is similarly derived from semi-empirical relationships, but it requires no local calibration. It is also most appropriate for the estimation of evaporation over larger areas of land or water, over time scales of several days to several years.

In southern Alberta, the models that have been commonly used by researchers and irrigation managers require routine weather data and readily estimated solar radiation as inputs. Experience shows that significant errors are generated when models that do not consider wind are used in the windy parts of southern Alberta, such as the vicinity of Lethbridge.

An intercomparison of areal estimates of evapotranspiration models is planned to operate under the auspices of the World Meteorological Organization. This program, which is the result of a proposal from Canada's National Hydrology Research Institute, should aid in defining the relative merits of the many techniques available for estimating evapotranspiration.

## REMOTE SENSING

There is some potential for the inference of evaporation rates by remote sensing from aircraft and space. The advantage of remote sensing is that it provides areal values, rather than point samples. Due to the long gestation period that remote sensing applications are undergoing, opinion varies widely as to the ultimate utility of these techniques.

A successful application of remote sensing from space was presented by Water Survey of Canada. It was demonstrated that an improved estimate of runoff from some mountain basins could be achieved using evapotranspiration estimates derived from satellite-measured net solar radiation. The Atmospheric Environment Service uses space-sensed lake surface temperatures to make its routine estimates of evaporation from the surface of the Great Lakes. Estimates of evapotranspiration have been made on land from emissivity in the visual and infrared bands, but not in an operational mode. The mapping of vegetation, snow cover and soil moisture indices is possible from satellites, and these are important inputs to the estimation of evapotranspiration.

## RESEARCH POTENTIAL

The Workshop, which represented a wide variety of applications, found the knowledge gaps have changed little in the past decade or two. Sensitivity analysis is needed to determine what each model will do and help establish logically which model is best suited for each application. Universal models which do not require local calibration from very limited data sets are needed. Further application of remote sensing should be pursued to help better understand areal relationships and possibly reduce overall monitoring costs. The concept of the groundwater system as a lysimeter of the annual accumulation of near and above-surface variable water load should be pursued to add a tool in the study of the hydrologic cycle. Finally, gaps remain in our instrument suite, particularly the lack of a robust, economical direct measure of evaporation and evapotranspiration.

More specifically, the Meyer Formula needs to be properly calibrated to its application on the Canadian prairies by a definitive water budget field study. The data gathering program should be designed to enable calibration or development of other models. For lake evaporation, convenient and accurate models of lake surface temperature are needed, because surface temperature remains difficult and expensive to monitor.

The Complementary Relationship Areal Evapotranspiration Model and other non-calibrated techniques require more testing to show how and where they can be applied. Further sensitivity analysis is required to determine how much error is caused by the various meteorological factors, including those which are not considered by the model.

Moisture losses from the evaporation of snow must be readily estimated in order to maintain a practical measure of potential soil moisture for crop growth or other applications. Further refinement is required to provide practical estimators of snow evaporation.

Remote sensing techniques require further development and further application. Microwave sensors are required to penetrate cloud for all-weather monitoring. In general, remote sensing results must be readily interpretable in order to be applied in resource management. For the up-coming Global Energy and Water-cycle Experiment (GEWEX), several areal measures will require higher accuracy than has been achieved in the past. This will require more precise sensors for radiation, precipitation, cloudiness, etc., as well as better techniques for analyzing these data and more accurate models for estimating things that cannot be directly monitored.

The consensus of the Workshop indicated there was a desire for something more representative of actual evaporation than the Class A Pan. The possibility of publishing a standard, acceptable estimate was suggested several times. This leads to the need to define the data available, the models which may be acceptable and the spatial scale that can be monitored. The alternative is to continue the search for a physically and conceptually robust technique of measuring evaporation that could be operated at a reasonable cost. Related to this need for evaporation measurement instruments is the continuing need for lower cost and better remote recording weather instruments in general to provide input data required by existing evaporation models

F.J. Eley
August 31, 1987.

## WELCOME TO PARTICIPANTS

by Dr. T. Milne Dick
Director of the National Hydrology Research Centre

Welcome to the National Hydrology Research Centre. We are all here this morning to discuss the common, but not well known phenomena of evaporation and evapotranspiration. Evaporation is a physical process. Transpiration is a biological process. Because it is hard to separate these two processes, they are very often taken together and called evapotranspiration.

I would like to welcome particularly, the biologists who are attending this workshop. Evapotranspiration obviously embodies both physics and biology and it is long overdue that the combined process be addressed in a cross-disciplinary way.

In this age of specialisation, we are fortunate to have both the Hydrometeorological Research Division and the National Hydrology Research Institute co-located in the Centre. The future success of environmental sciences depends on having good interaction between related disciplines, such as hydrology and meteorology. Closer collaboration is long overdue, and especially where evaporation is concerned, the added impact from biological sciences is needed to correctly assess the transpiration of water as part of the evaporation process.

I have just had a conversation with Don Gray, in which it became obvious that in the last 15 years or longer, we've got exactly nowhere with our understanding of evaporation.

It is obvious, of course, that evaporation plays a major role in regional water balances on the Prairies. After all, 75 percent of all water which falls on the land is evaporated. In Saskatoon and in this part of the world, evaporation exceeds the rainfall supply. So a small change in either of these two processes could be signifi-

cant to the water resources of this region. That is also true of other regions, but it is especially significant here. For that reason, our ability to understand and accurately predict water balances is becoming very important. There are some indications that past data may no longer give us any real security for the future. In other words, we cannot extrapolate what happened before as a predicition of what is going to continue to happen. Enormous sums of money may be at stake in this matter. For example, large-scale water diversions may be seen as a solution to an increasing imbalance in supply.

Welcome to Saskatoon, the Hub City of hydrological sciences. I hope we have some useful and interesting discussions on evaporation and transpiration during the next two days.

**SESSION I: USE OF EVAPORATION MEASUREMENTS AND ESTIMATES IN WATER RESOURCE MANAGEMENT.**

**Chairman - Roger Street, Canadian Climate Centre**

# EVAPORATION ESTIMATES IN WATER RESOURCE MANAGEMENT

by
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The Saskatchewan Water Corporation (SWC) was formed on July 1, 1984, with a corporate goal to manage the province's water and related land resources for the optimum economic and social benefits for the people of Saskatchewan. An important factor in meeting this goal is reliable evaporation and evapotranspiration estimates. Some of the major areas where these estimates are used by Sask Water are summarized below.

Evaporation estimates are an important factor in water supply studies. In these studies, evaporation estimates are used to determine the water availability, project feasibility and final design of the projects. Evaporation estimates are obtained from the 1985 PFRA report "Precipitation & Evaporation Tables, 1911 - 1984" and are transferred to the project site using the method described in the 1972 SSNB report "Water Supply For The Saskatchewan-Nelson Basin; Appendix 4; Hydrology". These evaporation estimates are calculated using Meyer's formula.

Evaporation and evapotranspiration estimates are also used in larger detailed hydrology studies. The evaporation data in these studies are usually used in some form of a water balance equation. In most studies the evaporation estimates at the project site are calculated using the same procedure described above for water supply studies. Recently, Sask Water has used Morton's model to supplement the PFRA evaporation data. For example, Morton's model was used for estimating evaporation and evapotranspiration in the Birch River Natural Flow Study.

A third area where evaporation estimates are used is in reservoir operations. In the day to day operation of the reservoir, no formal evaporation calculation is carried out. Instead, evaporation is combined with other parameters such as seepage, ungauged inflow, etc. to provide a correction factor used to balance recorded flows with reservoir elevations. This correction factor is usually estimated on a weekly basis. For long term operations and for apportionment purposes, reservoir evaporation is again calculated using the Meyer's formula.

The accuracy of the evaporation estimates affect the overall accuracy of the final study results. These estimates may be more critical in some studies than other. In detailed hydrology studies the estimated project evaporation values often need to be modified to obtain a water balance. This indicates that there is room for improvement in the present methodology.

Evaporation has a major impact on managing the province's water resources. There are over 8500 surface water projects with reservoirs in the southern half of the province with a total surface area of over 210,000 ha. With annual evaporation between 0.6 to 1.0 m, this works out to 1.2 to 2.0 million dams$^3$ on an annual basis. To put this number in to perspective, this is equivalent to approximately ten times the mean annual Souris River flow at the international boundary. On a hot summer day, the evaporation on Lake Diefenbaker can be equivalent to a flow of 100 m$^3$/s or more than twice the minimum flow requirement of 42.5 m$^3$/s through the City of Saskatoon.

# THE PPWB AND MEYER - AN EMPIRICAL RELATIONSHIP

by
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In June 1942, the Minnesota Resources Commission at St. Paul, Minnesota published a report written by A.F. Meyer entitled "Evaporation From Lakes and Reservoirs". In 1952, at the direction of the Prairie Provinces Water Board, the Hydrology Division of PFRA published PPWB Report No. 5 entitled "Evaporation From Lakes and Reservoirs on the Canadian Prairies", a study based on 30 years of meteorological records: 1921-1950. The PPWB report described how to adapt the Meyer Formula to the Prairie Provinces of Canada to provide estimates of evaporation losses from natural or artificial lakes and reservoirs. The working hydrologist had struck paydirt. Using this report he had a listing of monthly historic evaporation losses that could be applied to a similar listing of monthly streamflow to provide an estimate of the effectiveness of proposed or existing reservoirs.

The Meyers method is an empirical approach. It has shortcomings, but it works. Several of the methods suggested by the Atmospheric Environment Service, and by others, may provide more accurate estimates of the physical facts involved but they cannot be used to estimate historic evaporation because they rely on parameters that were not measured from 1910 to 1940.

When the SNBB study was started in 1968, two decisions were made concerning monthly evaporation estimates; firstly, should evaporation be considered in estimating reservoir potential and, secondly, how should evaporation be estimated? The SNBB Study personnel agreed to consider evaporation and they used the approach they knew - the Meyer Formula. The PPWB evaporation data base was extended back to 1912 and forward to 1967, and gross evaporation was estimated at a total of 17 base sites.

When the study was over, the responsibility of continuing to update the data base was assumed by the Hydrology Division of PFRA and they have kept the data base current since that time.

The Meyer Formula is now an entrenched fact of life. It has become an acceptable formula that provides evaporation estimates covering the same hydrologic period as most historic streamflow records. The results are accepted and used.

Now, in the late 1980s, it is time to review both the Meyer Formula and our use of it. The position of the PPWB Committee on Hydrology is:

1. The Meyer Formula is used because it is available and because it works.
2. The Committee is not convinced that there is a better alternative, although they have reviewed the recently developed Morton Formula.
3. When the Committee on Hydrology and/or the Board becomes convinced that there is a better way to estimate historic evaporation, they will recommend that the Meyer Formula be discarded and the new approach used.

Until that time, the Prairie Provinces Water Board will continue to use the Meyer Formula to estimate evaporation in the three Prairie Provinces realizing that it may not be the best way to estimate evaporation but remembering that, between the PPWB and Meyer, there is a long-standing empirical relationship.

# APPLICATION OF EVAPOTRANSPIRATION ANALYSIS IN AGRICULTURE

by
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The effects of weather on crop growth have always been the most varied and profound factors in the agricultural industry. The response by man was the birth and development of agrometeorology as a discipline which deals with many of these effects. The water balance of the soil-plant-atmosphere system has been a major topic in agrometeorology. Evapotranspiration, along with rainfall, is the driving force in this balance. This paper discusses the estimation of evapotranspiration from readily available weather data and its use as a crop production parameter.

Actual evapotranspiration (AE) can be estimated from daily weather records using a number of different computer models which are straight-forward, non-iterative and do not require extensive field measurements (Dyer and Boisvert, 1986). The most widely known of this type of semi-empirical model is to convert the potential evapotranspiration rate (PE) to an actual rate, as a function of soil moisture reserves. The potential rate describes water loss from a wet surface or a well watered plant canopy and is estimated from daily weather data using a wide range of equations.

When accumulated over time, AE is a good indicator of plant growth. Both photosynthesis and transpiration rates are more rapid when plant leaves are well supplied with water. High AE in response to high PE means that AE is also sensitive to heat unit accumulations, since both heat units and PE are functions of temperature. AE can be low relative to PE, when soil moisture reserves are low. AE estimates are therefore an indication of water stress or drought.

Accumulated AE estimates have been advocated and used by a number of previous authors as a means of estimating vegetative growth or biomass. Perennial forage yields were correlated with accumulated AE by Chapman and Brown (1966) and by Wallis et al. (1983). An index for annual field crop performance was developed by Dyer et al. (1984), in which adjustments were made for frost damage, heat stress

and timely planting and harvesting operations. The final output of this crop growth index, known as GRODEX, is an estimate of effective seasonal AE in mm of water.

GRODEX has been used in two agro-economic studies, where the agricultural sector performance was being related to marketing and cost of production factors (Brinkman, 1984 and Gilmour, 1985). Both of these studies found that GRODEX contributed significantly to explaining annual variance in net farm productivity. GRODEX estimates were run for 87 weather stations from 1961 to 1985.

The material referred to here does not represent new or innovative research. It illustrates an aspect of agrometeorology which can now be considered as a technology which can contribute to improved management of agricultural resources. One potential research area which could enhance this technology is in the relationship between vegetative growth and transpiration rates. Another area would be to characterize root development and growth patterns for major crops, since these patterns can be used directly in soil moisture budget models (Dyer and Dwyer, 1982). These examples suggest that there are still practical benefits to be gained from applied research in evapotranspiration.

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# EVAPORATION AND EVAPOTRANSPIRATION ESTIMATES

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## INTRODUCTION

The purpose of this paper is to familiarize those attending the Workshop with the methodologies employed by the Water Resources Branch, Manitoba Department of Natural Resources, to estimate areal evaporation (E) and evapotranspiration (ET) for water resources management. An associated purpose is to convey an opinion on the appropriateness and adequacy of the various methodologies available to estimate E and ET. Estimation of ET is also discussed from a hydrologic modelling perspective. Evaporation is dealt with first, followed by evapotranspiration.

## DESCRIPTION AND FINDINGS

### a) Evaporation

The major uses of evaporation estimates in Manitoba include the design of water storage reservoirs, the development of rule curves for the operation of reservoirs, forecasting of water supplies, and miscellaneous uses such as the investigation of seepage losses from lagoons and reservoirs.

The Meyer mass transfer formula has generally been used to estimate monthly evaporation losses from lakes and reservoirs. The value of "C" used in the formula is generally 11.0 and water temperatures are computed from monthly mean air temperatures using regression equations developed on Lake Of The Woods. During the 1980's some modifications of the basic Meyer estimates have gradually come into use. These include monthly correction factors based on the size and depth of lakes. The factors are based on a qualitative assessment of observed

surface water temperatures of water bodies compared with those computed by regression equations. The monthly factors are as follows:

| | April | May | June | July | Aug | Sept | Oct |
|---|---|---|---|---|---|---|---|
| Large Lakes: | 0.55 | 0.65 | 0.85 | 0.85 | 0.85 | 0.90 | 1.00 |
| Dugouts and Small Reservoirs: | 1.50 | 1.70 | 1.20 | 1.00 | 0.90 | 0.70 | 0.50 |

For small lakes or large reservoirs Meyer values are used without adjustments. For small dugouts and reservoirs, 70 percent of pan evaporation has been more frequently used in recent years instead of adjusted Meyer values. When estimates of daily evaporation are required, a mass transfer formula developed for Lake Hefner is generally used.

With regard to the appropriateness of the various methodologies for small lakes, some comparisons have been done using data for the month of August 1984 for Winnipeg. The Manitoba Meyer method and the PPWB Meyer method, using monthly mean inputs, produced 178 mm and 180 mm respectively. AES small lake evaporation (approx. 70% of pan evap.) was 143 mm. The Lake Hefner formula, using daily data as recorded, and the Meyer computed water temperature produced 129 mm.

To illustrate the possible error associated with the use of monthly mean inputs, the August 1984 daily data for Winnipeg was re-arranged so that a) high daily winds were associated with high daily vapour pressure gradients and b) lighter daily winds were associated with low daily vapour pressure gradients. The resultant computed evaporations for the month were 142 mm and 106 mm respectively.

b) Evapotranspiration

The major uses of areal evapotranspiration (ET) estimates are streamflow forecasting and groundwater aquifer yield analysis. The objective for streamflow forecasting is to perform a soil moisture accounting since runoff is highly affected by soil moisture.

Due to the difficulties of estimating ET, simple index procedures such as the antecedent precipitation index (API) are still used to obtain an index of soil moisture. API is weighted summer precipitation, usually expressed as a percent of

normal. Weights increase with time to account for the decreasing ET opportunity from the early summer to the fall. Other methods employed to estimate soil moisture include the well known Thornthwaite method and the somewhat more complex procedure in the Hydrologic Simulation Program Fortran (HSPF) streamflow simulation model.

The method employed by HSPF, a leading streamflow simulation model in North America, assumes that there is a potential evapotranspiration "demand" (PE) which can be approximated by (0.7 x pan evap.). The model then attempts to meet the demand on a priority basis, according to model parameters obtained from general experience or the calibration process. ET from interception storage is given first priority, followed by that from riparian vegetation, the upper zone, groundwater and the lower zone. Lower zone ET is most significant since this involves the major root zone of crops. To estimate ET from the lower zone, the model first computes a maximum value of ET opportunity for a given lower zone soil moisture storage, LZS, and a long-term benchmark value of LZS known as LZSN.

$$\text{MAX. ET} = [0.25/(1.0\text{-LZETP})] * (\text{LZS/LZSN}) \quad (1)$$

The lower zone evapotranspiration parameter LZETP is obtained through calibration and may contain monthly factors to account for the typical relative state of plant growth through the growing season. The following monthly factors were used in calibrating some Manitoba watersheds:

| May | June | July | August | September | October |
|---|---|---|---|---|---|
| 0.10 | 0.21 | 0.36 | 0.28 | 0.28 | 0.20 |

ET for a given time interval is then estimated from a graph relating MAX. ET to PE and the percentages of the basin area having ET opportunity less than MAX. ET.

Manitoba applied the HSPF model to four smaller watersheds. The accuracy of the streamflow simulations was about the same as that using relatively simple index models. It was difficult to determine what portion of the difference between simulated and recorded streamflows was due to errors in ET estimates. A comparison between simulated and measured soil moisture at freeze-up in the fall produced fair results but was inconclusive due to the unreliability of the few available point soil moisture measurements.

## CONCLUSIONS

### a) Evaporation

Despite the considerable errors likely associated with evaporation estimates, present methodologies appear to be providing good enough estimates for water resources management in most instances. This is likely due to equivalent or even larger errors in the other equally important components of the water balance of many lakes and reservoirs, namely precipitation, inflows and outflows.

There does appear to be a potential to improve evaporation estimates with a minimal effort with existing data, by using daily or hourly data and computation steps rather than the monthly interval generally used.

There appears to be a need for different methodologies for evaporation calculations for water bodies which are greatly different in surface area and/or depth.

### b) Evapotranspiration

Conventional hydrologic models, which are generally based on the assumption that plants are "wicks" which transport soil moisture to the atmosphere in order to meet the PE demand, probably don't provide accurate estimates of evapotranspiration. The empirical relationships used to estimate ET in a model such as HSPF can't be accurately calibrated due to spatial unknowns in watershed characteristics and inputs. Many of the latter, such as the effective drainage area, soil infiltration rates and the amount and rate of rainfall or snowmelt are not well known and introduce considerable error into streamflow simulations. Errors in evapotranspiration estimates are therefore not discernible over shorter time periods up to a month or season. Spatial information on actual soil and subsoil moisture storages would be required to calibrate the ET component of the model and even this would be insufficient if the specified empirical relationship is incorrect. It might be better to compute ET from first principles by determining the behaviour of plant stomata under various soil and atmospheric conditions.

## IMPLICATIONS FOR FURTHER RESEARCH

### a) Evaporation

As a first step it might be wise to review alternate mass transfer techniques based on daily input data and a daily computational time step. The improvement of evaporation estimates may not warrant a great deal of research if there are no firm prospects to improve the estimates of the other water balance components such as rainfall and streamflow.

# EVAPORATION AND ITS ROLE IN THE APPORTIONMENT OF BOUNDARY WATERS IN SOUTHERN SASKATCHEWAN

by
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The intent of this paper is to inform workshop attendees of the methods presently used by the Water Resources Branch (WRB), Regina to estimate evaporation particularly as it relates to apportionment of boundary waters.

## BACKGROUND

The Boundary Waters Treaty of 1909 and the Prairie Provinces Water Board Master Agreement on apportionment of 1969 define the division of waters between Canada and the USA, and the provinces of Alberta, Saskatchewan, and Manitoba. Basically, the Treaty and the Agreement both stipulate that the water division shall consist of an equal sharing, between the upstream and downstream parties, of the natural flow of the watercourse as calculated at the boundary. WRB, Regina is responsible for monitoring recorded flows and calculating natural flows at the following points: Battle, Middle, and Lodge Creeks and the Qu'Appelle River at the interprovincial boundaries and; Lodge and Battle Creeks, and the Frenchman, Poplar, and Souris Rivers at the international boundary.

Natural flow is what the flow would be if there were no influence by man. In very general terms the natural flow is computed by adding all water that is diverted from the river to the recorded flow at the boundary, and subtracting all water that is released to the river upstream of the boundary.

The construction of a reservoir with the resultant impoundment of runoff greatly increases the amount of water lost to the atmosphere. This increase in evaporation is considered a depletion of the natural flow and is charged to the jurisdiction where the loss occurs. Losses due to evaporation can be significant representing about a three-fourths to one metre drop in a Southern Saskatchewan reservoir's water level annually. For the lakes in the Qu'Appelle River basin this amounts to a loss of about 150,000 $dam^3$ of water annually. Cypress Lake contained 70,800 $dam^3$ of water on April 30, 1987. Evaporation can be expected to reduce that storage to about 50,000 $dam^3$ by October 31.

## EVAPORATION ESTIMATES

Reservoir evaporation on the eastern tributaries of the Milk River is determined by utilizing the evaporation data collected at meteorological stations at Altawan and Val Marie established in co-operation with the Atmospheric Environment Service (AES). The evaporation station consists of a class "A" evaporation pan, rain gauge, maximum and minimum air and water thermometers and a wind velocity indicator. The water in the evaporation pan is maintained at a constant level by either adding or removing water as required on a daily basis. For the purposes of the natural flow computations, the net reservoir evaporation is 0.70 of the net pan evaporation which is simply the daily change in the pan water level.

Precipitation is included in the definition because with the impoundment more water is captured than would reach the stream under natural conditions. However, the entire amount of precipitation is not added to the system as under natural conditions some of the precipitation falling on the area now covered by the reservoir would have reached the stream. The amount of creditable precipitation is taken as 0.70 of the total precipitation, which is the same coefficient used in converting pan evaporation to reservoir evaporation.

In the Souris River basin, net reservoir evaporation is estimated based on daily class "A" pan evaporation data and precipitation data. The methodology is similar to that used for the eastern tributaries of the Milk River except that variable conversion factors are used rather than a constant of 0.70.

In the Qu'Appelle River basin reservoir evaporation is estimated using upper Lake Diefenbaker shallow layer evaporation as computed by AES using Meyer's equation. Evaporation from Eyebrow Lake and Buffalo Pound Lake is estimated based on a function of the reservoir surface area and the Lake Diefenbaker shallow layer evaporation multiplied by 1.10. For the remaining Qu'Appelle lakes the evaporation is computed using the same methodology. However, evaporation is computed only for the incremental area greater than the area which would occur naturally. These lakes are maintained about one-third of a metre higher during summer and fall than would occur naturally.

## SUMMARY OF DISCUSSION IN SESSION I, May 20, 1987

1. Meyer Formula - Bruce Godwin

   Q. Where does it not work?

   A. In smaller reservoirs. Off the prairies, other models work better.

   Q. Do you have available quantitative assessments based on water balance in reservoirs.

   A. Yes, there are several.

2. Effects of Land Use Change on the Prairies

   Morton expressed concern about the need for further research on soil-plant-atmosphere relationships. (Present knowledge may be adequate for day to day water resources management, but it is inadequate for forecasting the effects of land use change.)

   Street agreed that there are multiple uses for evaporation estimates, and that high precision will be required to deal with the effects of land use changes.

**SESSION II: THE MEASUREMENT OF EVAPORATION AND EVAPOTRANSPIRATION.**

**Chairman - Wally Nicholaichuk, NHRI.**

## A COMPARISON OF EVAPORATION ESTIMATES FROM THE SASKATCHEWAN RESEARCH COUNCIL'S CLIMATOLOGICAL REFERENCE STATION

By
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Four evaporimeters have measured the water vapour flux at the Climatological Reference Station of the Saskatchewan Research Council. It is the purpose of this report to provide a brief overview of the performance of these instruments.

The Saskatchewan Research Council (SRC) has operated a Climatological Reference Station (CRS) on the University of Saskatchewan grounds for nearly 25 years, prior to this the physics department of the University of Saskatchewan operated the station, beginning near the turn of this century.

The daily evaporation from these four evaporimeters was compared during the summers of 1975 to 1985. Statistical analyses were conducted on the evaporation data for the days from June to September, so there were more than 1000 evaporation measurements available for each instrument. For the purpose of comparison, water loss from the four evaporimeters was converted into water flux ($Kgm^{-2}D^{-1}$). It was the purpose of a recent study (Qingpei and Shewchuk, 1986) to report on the comparative results from these instruments. The evaporimeters are the Class "A" pan, black flat plate (Bellani) atmometer, white sphere atmometer and black sphere atmometer.

The yearly water flux from the Class "A" pan was expressed as $X_1$. $Sx_1$ was the standard deviation of $X_1$ and $N_x$, the number of samples. Fluxes from the other instruments were $X_2$, $X_3$ and $X_4$ respectively (Table 1). T-Testing indicated that the difference of means in each pair exceeded the level of significance except that of $X_1$ and $X_3$. The value of t from $X_1$ and $X_3$ was 2.33, which just reached the 5% level of significance ($t_{0.01} = 2.33$). That is to say, the variation of water flux of the Class "A" pan is similar to that of the white sphere.

Regression analyses to compare evaporimeters in pairs were performed on the water flux data. The data of Table 2 show the correlation coefficients from all pairs.

The correlation coefficients between the Class "A" pan and the Bellani plate were lower than that between it and the other atmometers. It was apparent that they were influenced by different microclimate conditions. The Bellani plate is very responsive to wind, but less so to net radiation. The results suggest that the Bellani plate observations are less consistently related to the evaporation of Class "A" pan, and that different conversion factors may be required for different ranges of evaporation amounts.

## REFERENCE

Fei Qingpei and S.R. Shewchuk, 1986. A comparison of evaporation estimates from the Climatological Reference Station of the Saskatchewan Research Council. SRC Technical Report 190, E-906-7-B-86.

Table 1. Yearly Mean and Standard Deviation of Water Fluxes ($Kgm^{-2}D^{-1}$)

| YEAR | Class "A" Pan ($X_1$) | | | Flat plate ($X_2$) | | | White ($X_3$) | | | Black ($X_4$) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $X_1$ | $Sx_1$ | $Nx_1$ | $X_2$ | $Sx_2$ | $Nx_2$ | $X_3$ | $Sx_3$ | $Nx_3$ | $X_4$ | $Sx_4$ | $Nx_4$ |
| 1975 | 5.97 | 2.51 | 111 | 11.78 | 5.37 | 111 | 5.68 | 2.76 | 111 | 7.55 | 3.34 | 111 |
| 1976 | 6.84 | 2.92 | 113 | 19.23 | 8.83 | 113 | 7.29 | 3.61 | 113 | 9.01 | 3.89 | 113 |
| 1977 | 5.71 | 2.81 | 121 | 19.52 | 9.53 | 121 | 5.82 | 2.99 | 121 | 7.56 | 3.72 | 121 |
| 1978 | 6.42 | 3.09 | 122 | 26.27 | 11.38 | 122 | 7.14 | 3.34 | 122 | 8.48 | 3.82 | 122 |
| 1979 | 6.48 | 2.40 | 117 | 16.17 | 6.27 | 117 | -- | -- | 0 | 8.95 | 3.11 | 117 |
| 1980 | 6.20 | 2.82 | 101 | 13.39 | 6.93 | 101 | 6.24 | 3.13 | 101 | 8.58 | 3.99 | 101 |
| 1981 | 6.80 | 3.13 | 122 | 11.53 | 6.38 | 122 | 7.82 | 4.03 | 122 | 9.59 | 4.53 | 122 |
| 1982 | 5.85 | 2.62 | 103 | 12.52 | 5.26 | 103 | 5.93 | 2.59 | 103 | 7.75 | 3.24 | 103 |
| 1983 | 6.83 | 2.79 | 100 | 21.95 | 8.89 | 100 | 7.28 | 3.16 | 100 | 9.04 | 3.64 | 100 |
| 1984 | 8.02 | 3.80 | 113 | 31.17 | 14.03 | 113 | 8.32 | 4.26 | 113 | 10.44 | 4.81 | 113 |
| 1985 | 6.01 | 2.79 | 108 | 12.21 | 5.50 | 108 | 6.20 | 2.79 | 108 | 7.99 | 3.24 | 108 |
| TOTAL | 6.47 | 2.96 | 1231 | 17.89 | 10.57 | 1231 | 6.79 | 3.43 | 1114 | 8.64 | 3.88 | 1231 |

Table 2. Correlation Coefficients Between Daily Water Flux from Different Evaporimeters

| YEAR | Evaporimeters Correlated | | | | | |
|---|---|---|---|---|---|---|
| | $X_1$ $X_2$ | $X_1$ $X_3$ | $X_1$ $X_4$ | $X_2$ $X_3$ | $X_2$ $X_4$ | $X_3$ $X_4$ |
| 1975 | 0.86 | 0.82 | 0.84 | 0.98 | 0.98 | 0.99 |
| 1976 | 0.77 | 0.77 | 0.78 | 0.99 | 0.99 | 0.99 |
| 1977 | 0.92 | 0.92 | 0.93 | 0.99 | 0.99 | 0.98 |
| 1978 | 0.88 | 0.86 | 0.87 | 0.98 | 0.99 | 0.98 |
| 1979 | 0.84 | -- | 0.81 | -- | 0.95 | -- |
| 1980 | 0.91 | 0.86 | 0.90 | 0.96 | 0.98 | 0.96 |
| 1981 | 0.77 | 0.84 | 0.87 | 0.66 | 0.74 | 0.98 |
| 1982 | 0.74 | 0.74 | 0.71 | 0.97 | 0.91 | 0.93 |
| 1983 | 0.87 | 0.84 | 0.84 | 0.98 | 0.97 | 0.97 |
| 1984 | 0.79 | 0.83 | 0.85 | 0.95 | 0.99 | 0.98 |
| 1985 | 0.88 | 0.85 | 0.87 | 0.98 | 0.97 | 0.97 |
| TOTAL(R) | 0.708 | 0.831 | 0.846 | 0.785 | 0.798 | 0.970 |
| Number of Samples | 1231 | 1114 | 1231 | 1114 | 1231 | 1114 |

# EVAPORATION IN THE POST-MELT PERIOD: A CASE STUDY

by
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A field program was undertaken by the Division of Hydrology, University of Saskatchewan, to study the disposition of infiltrated meltwater in the period following the disappearance of the seasonal snowcover to the time of seeding. During this six-to-nine week period a soil moisture profile can undergo significant changes because of: withdrawal of water from the surface layer due to evaporation, downward movement of water from the surface layer to the root zone, or drainage from the root zone, and infiltration of precipitation (rain and/or snow).

During the observation period 1978 to 1985 soil moisture changes in the post-melt period were monitored at approximately 160 sites. It was found that evaporation is the dominant process affecting soil moisture changes in this period. All the sites (100%) showed evaporation losses; at only 54% of the sites was the soil thaw sufficiently rapid to allow some of the infiltrated meltwater to move deeper into the root zone; only 24% of the sites were sufficiently moist to allow drainage below the measurement zone (~1.2m).

The magnitude of the evaporation losses (EVAP) was significant when compared to the gains obtained from meltwater infiltration (INF) and precipitation (PPT). For fallow lands Evap was greater than INF at 94% of the observed sites; the average infiltration to fallow was 20.7 mm while the average evaporation loss during the post-melt period was 51.9 mm. The average ratios INF/EVAP being 0.4. Cracked soils not only allow for significantly greater INF, but allow the meltwater to penetrate deeper into the soil profile thus protecting it from being lost to EVAP.

Observed daily evaporation rates in the first days following the disappearance of the snowcover were as high as 9 mm/d from fallow and 7 mm/d from stubble. Evaporation rates diminished during the period as the soil surface dried. On average, amounts of water equivalent to the average infiltration were lost to evaporation

within a 7-day period on fallow and a 16-day period on stubble. The average daily evaporation rates for the total post-melt period were 1.2 mm/d for fallow and 0.9 mm/d for stubble.

The evaporation losses incurred in the post-melt period appear to be affected mostly by the amount of precipitation received and the length of the period.

Some implications of these results important to agriculturalists are:

1. In many years the amount of evaporation in the post-melt period exceeds the gains from snowmelt infiltration. In these cases snowmelt infiltration serves mainly to compensate the evaporation losses, and the moisture status of a soil to the seeding depth at the time of seeding, will depend largely on precipitation received in the post-melt period.
2. The results confirm that in order to make effective use of the snow water resource, it may be necessary to apply snow management on naturally-cracked soils or in conjunction with some practice, such as subsoiling, which induces cracking. Cracked soils not only allow a greater amount of meltwater to infiltrate, but also allow the water to penetrate deeper into the soil, away from the surface layer which undergoes drying due to evaporation.
3. Any soil moisture model whose purpose it is to estimate soil moisture reserves at the time of seeding must consider these evaporation losses occurring during the post-melt period.

# AREAL ESTIMATES OF EVAPORATION FROM AIRBORNE WATER VAPOR FLUX MEASUREMENTS

by
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A major difficulty in any water balance study is the estimation of evaporation. In the last seven years Agriculture Canada, the National Aeronautical Establishment of NRC and McGill University have made considerable progress in the area of airborne measurement of $CO_2$ and $H_2Oo$ analyzers.

In 1985, it was demonstrated that by flying four runs over a distance of 4 km of homogeneous crop at either 10, 25 or 50 m the measured $CO_2$ and water vapour flux values were very similar to those obtained with a ground based flux system. It was demonstrated that consistent measurements of $CO_2$ and water vapour flux could be obtained for even smaller areas by doing repeated passes over the area of interest.

In 1986, an extensive evaluation of $CO_2$ and $H_2O$ flux measuring systems was carried out on the ground in conjunction with the airborne flux measuring program. The accuracy of these flux measurements will be discussed. Measurements of $CO_2$ and $H_20$ flux were also obtained simultaneously with radiance data from Landsat V. The potential of these measurements to develop and test algorithms for estimating evaporation on a regional scale will be discussed.

With the current version of the airborne system, $CO_2$, water vapour, sensible heat and momentum fluxes and incoming solar radiation are measured. For the 1987 measuring program a PRT-5 radiation thermometer will be added to obtain surface temperature measurements and incoming and reflected radiation at 660 and 730 milli-microns to obtain greenness index measurements. This system will be used in FIFE (First International Field Experiment in the International Satellite Land Surface Climatology Experiment).

# AN OPERATIONAL BOWEN RATIO SYSTEM FOR DETERMINATION OF EVAPOTRANSPIRATION

by
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The Bowen Ratio or energy balance method is a well known technique of partitioning the energy budget to determine evapotranspiration (ET). The energy budget is based upon the principle of conservation of energy and is usually expressed as $R_n - G - H - L_e = 0$, where $R_n$ is the net radiation, G is the soil heat flux, H is the sensible heat flux and $L_e$ is the latent energy flux due to evaporation. The direct measurement of H and $L_e$ is possible only with the eddy correlation technique. The sensors available for eddy correlation have improved greatly in recent years, however they are not yet suitable for long term unattended operation. The Bowen Ratio system was designed to meet these requirements. The system is complete, self-contained and will operate in remote locations.

Table 1 lists the parameters measured and the sensors used. Vapour concentration is measured at two levels with a single cooled mirror dew point hygrometer (Modified General Eastern Dew-10). Air is drawn from both heights continuously. The air is drawn through the cooled mirror and is switched from one height to another every two minutes. A 45 second stabilization period is used between measurements of the two levels. A two liter mixing chamber is included in each line yielding a 5 minute time constant for a flow rate of 0.4 l/min. The dewpoint temperature is measured every second and the vapor pressure calculated by the 21X data logger. The resolution of the 21X dewpoint temperature measurement is $+/0.003^{o}C$ over a $+/-35^{o}C$ range. The critical factor is the stability of the control of the Dew-10, approximately $0.05^{o}C$, yielding less than +/-0.01kPa vapour pressure resolution over most of the environmental range.

Air temperature is measured at two heights with 0.001 inch chromel-constantan thermocouples. The thermocouples are not aspirated, but due to their small size, experience less than $0.2^{o}C$ and $0.1^{o}C$ heating at 0.1 and 1 $ms^{-1}$ wind speeds, respectively, under 1000 $Wm^{-2}$ radiation. More importantly, the symmetry of their junctions at the two levels hold radiation errors in the temperature gradient measurement to 0.01 - $0.02^{o}C$.

The output from the net radiometer is averaged over the same period as the vapour pressure and temperature differences. Heat flux plates should be buried in the soil at 5 to 10 cm to reduce errors due to vapor transport of heat around the plate. The average temperature of the soil layer above the plate is measured. The heat flux at the surface is then calculated by adding the heat flux measured by the plate to the energy stored in the soil layer.

The current requirements of the components of the Bowen ratio system are the following: 21X, < 5 mA; pump, 60 mA; and the cooled mirror, 150 - 500 mA. The SX20 solar panel and a 70 amp-hour battery provide a continuous current of 300 - 500 mA. The solar panel is mandatory unless the system is only used for periods of 2-3 days.

The sensor arms, instrumentation enclosure and solar panel all mount on the CM10 tripod. The net radiometer arm is fixed to either sensor arm. An optional crossarm at the top of the tripod allows mounting for windspeed and direction sensors, useful in detecting periods when the fetch is marginal.

**TABLE 1**

| PARAMETER MEASURED | SENSOR |
|---|---|
| Air Temp (2 levels) | Fine wire thermocouple |
| Water Vapour (2 level) | Cooled mirror dew point hygrometer |
| Net Radiation | Net Radiometer |
| Soil heat flux | Thermopile heat flux plate |
| Soil Temp, layer average | Averaging Thermocouples |

# EVAPORATION AND EVAPOTRANSPIRATION MEASUREMENTS USING REMOTE SENSING

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For both evaporation and evapotranspiration, the task of remote sensing is to replace one or more parameters used in the calculation equations. Remote sensing provides the ability to do a lot very quickly once the data is in the computer system but it requires considerable capital expenditure to capture the data from the satellite and process it. The tools for analyzing data in the remote sensing area are now very powerful and quick. Standardized computer programs make remote sensing very efficient compared to traditional site measurements and areal estimation.

Since evaporation is 80% of the outgoing part of the hydrological cycle and evapotranspiration is 20%, evaporation has received the bulk of the research attention. With the success enjoyed by evaporation researchers, more has been done in remote sensing evapotranspiration in the last 3 years than in the last 20 years.

When considering remote sensing projects, one must be always cognizant of the space and time scales of the events to be measured and the correct choice of the satellite to match these considerations. For evapotranspiration, the time scale is one hour to one day. The space scale is about 100 m. Soil moisture changes take place over an area of about one kilometre and over about 12 hours to 3 days. These requirements put considerable constraints on the choice of satellites. None of the current satellites can provide proper coverage for evaporation or evapotranspiration; only soil moisture. The suggested satellite choice for soil moisture is NOAA - AVHRR. If airborne data can be afforded then passive microwave is the choice.

When one looks at the equations which are used in calculating evaporation and evapotranspiration, the present research is going into measuring soil moisture by Synthetic Aperture Radar (SAR) and Gamma radiation sensors. Gamma or passive microwave is presently available on the NIMBUS satellite (and on DMMS). The

Heat Capacity Mapper Satellite (HCMS) is capable of providing the energy balance of the surface. Vegetation cover for potential transpiration can be determined by a process called Normalized Difference Vegetation Indices mapping. The vapour flux can be measured by the NOAA satellites, but the data analysis is very time consuming. No other parts of the soil/plant/atmosphere cycle can be sensed by satellite.

There are numerous world wide experiments going on at the moment in global monitoring which must measure evaporation. In addition, one of the inter-comparison tools will be remote sensing, therefore, within the next few years better algorithms will be available for evapotranspiration calculations.

# ESTIMATING EVAPOTRANSPIRATION THROUGH THE USE OF REMOTE SENSING

by
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Evapotranspiration (ET), spatially estimated by remotely sensed means, would be a useful input to a weekly water budget that is currently run at the Hydrometeorology and Marine Division. This presentation provides a classification of published techniques according to the remote sensor's wavelength band.

A) The iterative energy-balance-model inversion technique uses infrared (IR) data to estimate the surface temperature. This model, when run iteratively until it matches the surface temperature, gives a solution for the latent heat flux. The number of computations can be quite large if the model is run over each pixel.

B) In the heat transfer equation approach, visual (VIS) and IR data are converted to surface temperature and net radiation that are then fed into the diffusion equation for the latent heat flux. For constant meteorological conditions and a surface homogeneous in emissivity and roughness, ET over dark and cool surfaces is expected to be higher than over bright and warm surfaces. This method was developed for daily estimates.

C) Greater vegetation (larger number of stomatae) would result in reduced canopy resistance to the flux of water vapor. Leaf area index (LAI), a measure of the amount of biomass, is proportional to the normalized difference index (ND) obtained from near-infrared (NIR) and IR channels. Simulations have illustrated the use of remotely sensed maps of transpiring vegetation to generate maps of ET.

D) The addition of passive microwave estimates for the topsoil water content was suggested in recent simulations.

As remote multisensor algorithms are being developed, the following aspects must be considered:

- Air temperature, moisture and wind are usually required in the computations
- The methods were developed for cloud free conditions only.
- Direct latent heat flux measurements, representative of a remotely sensed pixel, are requested for calibrations.
- Time and space resolutions of sensors carried by various platforms lead to a variety of approaches.
- Recommendations for the choice of sensors on future satellites could be made.

# ESTIMATION OF PRECIPITATION, NET RADIATION, EVAPOTRANSPIRATION AND RUNOFF FROM GOES DATA

by
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As part of the study to examine the extent to which Water Survey of Canada streamflow data i.e. basin runoff can be estimated from data from other sources, estimates of precipitation, net radiation, and evapotranspiration were made using GOES visible band digital data (GOES is an acronym for Geostationary Operational Environmental Satellite). GOES forms images in two frequency bands, the visible (0.54-0.74 um) and infrared (10.5-12.5 um). The sampling rate was one image per month taken as near local noon as possible on the last day of each month. The study was conducted over 48 months, from November 1978 to October 1982 for the southern part of British Columbia, about 800 km west-east and 300 km north-south.

Each of the 48 images was geographically registered (navigated) in order that the digital values of each picture element (pixel) could be associated with a position on the earth's surface, that is, the pixel coordinates could be related to latitude and longitude.

The next step was establishing relationships or transfer functions between conventional ground-based observations and the digital counts data from GOES. For 85 precipitation stations in the study area, each station was placed at the centre of a 21 by 21 pixel square. For each image the digital values for each pixel were extracted. If the mean value for the digital counts over the 21 X 21 pixel square were greater than 110, the sky was taken to be cloudy, thus a candidate for precipitation and the mean value was added to a total for that precipitation station. A bivariate plot of 85 points was made for 48 month total precipitation and accumulated mean digital counts value. The plot could be segmented i.e. the plotted points clustered into four regions corresponding to geographic regions in the study area. For each geographic region a regression equation was developed for 48 month precipitation as a function of mean digital counts. Using the geographically appropriate regression equation allowed an estimate of precipitation for a given basin.

To estimate the energy available for evapotranspiration the incoming shortwave radiation, the outgoing shortwave radiation and longwave radiation were estimated.

To estimate the incoming shortwave radiation, on each day for which an image was available, the daily global solar radiation field (RF1) was regressed against the mean digital counts value in a 21 pixel by 21 pixel square about each of the four available radiation stations. As only 48 of a possible 1461 days were sampled, the total incoming radiation estimated from the 48 regressions was multiplied by 1461/48. The total estimated radiation for the four stations was within 5% of the total observed radiation. Using the 48 regression equations the total incoming shortwave radiation could be estimated for each of the 65 basins in the study area.

To estimate the outgoing shortwave radiation an albedo or reflection coefficient is required for each basin. To develop a relation between known albedos and digital counts, digital counts from areas of 10 pixels by 10 pixels of known surfaces such as water, forested areas, and new snowfields were regressed against albedos.

The reradiated longwave radiation was assumed to take place only on cloud-free days, i.e. those with mean digital counts less than 110. On cloudless days the radiation was estimated from the Stephan-Boltzmann equation with Emissivity=1 and basin temperature estimated from a regression equation using latitude, longitude and elevation. The percentage of cloud-free days times 1461 provided the total time for reradiation.

The net of the incoming and outgoing radiation was taken to be the energy available for potential evapotranspiration for each basin. This potential evapotranspiration together with the basin precipitation estimate were input to Turc's Formula to give an estimate of actual evapotranspiration for each basin over the 48 months.

Runoff for each basin was estimated as precipitation minus actual evapotranspiration. Differences between observed runoff and runoff estimated using GOES data were less than differences between observed runoff and mean regional runoff, indicating that GOES data has provided improved estimates of runoff over those from simple regionalization.

## SUMMARY OF DISCUSSION IN SESSION II, May 20, 1987

1. Atmometers Stan Shewchuk

   Q. What corrections were applied to the Class A Pan measurements.

   A. A correction was applied for wind velocity and temperature, but not the factor reducing it to 'lake evaporation'.

   Q. Why use Bellani plate or spheres rather than a pan.

   A. These atmometers are more relevant to crop evapotranspiration, while the pan is more representative of lake evaporation. The practical advantage of the white (Livingstone) sphere over pans are simply the small size and the convenience of supplying small amounts of water. They also have less problem with sheltering, since they are placed above the ground, usually at 'screen height'. The disadvantages of the spheres are:

   i) they break easily in a frost (although replacements are not expensive); and

   ii) they are more variable relative to other measures for short time scale (of less than one month).

   Q. Are you planning to automate your evaporation measurements with white spheres?

   A. Sask. Res. Council is not planning to automate the small atmometers in the near future.

2. Airborne Eddy Correlation Measurement Ray Desjardins

   Q. Is there a storage of heat and water vapour in the 50m below flight level?

   A. Water vapour storage is not a problem, but heat storage can be a concern.

   Q. How do you sort out the evaporation from the area in question from the vapour advected in horizontally?

   A. That cannot be done. In order to minimize the possible effects of advection, measurements are only made where the width of the field is at least 50 times the flying height.

3. Bowen Ratio System C. Labine

   Q. Can it work well below freezing?

   A. It should operate well to -10$^{o}$C. except for possible pump problems. Humidity and evaporation rates become very small values at cold temperatures.

   Q. How long can the interval be between servicings?

   A. Experience with prototypes indicates two weeks.

4. Airborne Gamma Snow Survey from J. Whiting's paper

Q. How practical is airborne gamma for soil moisture surveying?

A. It costs about $300 per line-mile.

Q. The U.S. National Weather Service has used it operationally for snowmelt runoff forecasting. Would it require many flight lines to do it operationally for soil moisture, which varies quickly over time?

A. It would require twice per day surveys to take care of nocturnal variations, and 100m accuracy.

Q. How do benefits compare to the cost?

A. The cost is about double that of ground observations, and the data takes considerable time to process.

5. Evapotranspiration- inference from space

Comment: There is a good correlation between a vegetation index and accumulated precipitation inferred from satellite observations, and yield of crops in Saskatchewan. This relationship may lead to an estimate of evapotranspiration from space.

6. Satellite (NOAA) Temperatures N. Bussieres

Comment: There have been wrong temperatures supplied from NOAA satellite data. This was particularly true during a special observation program, when the satellite was adjusted for higher resolution, changing the infrared temperature calibration, and the change was not communicated to the researchers.

Comment: The problem may be that the satellite temperature maps are calibrated to screen temperature instead of soil temperature.

## SESSION III: REPORTS OF THE WORKING GROUP SESSIONS

**May 20, 1987**

**Chairman - R. Lawford, AES., Saskatoon**

The workshop was split in to three Working Groups to carry on discussions for a half-hour each of the two days. The Working Groups were assigned a series of questions leading to an assessment of research required in support of improving the estimation of evaporation and evapotranspiration. The general themes of the questions considered were: (i) are present methods of estimating or measuring evaporation accurate enough?; (ii) what physical processes are represented by measurements and estimates of evaporation and evapotranspiration?; (iii) can modern remote sensing and instrumentation improve estimates of evaporation and evapotranspiration?

The report below shows the questions presented to each working group and a summary of what was discussed and reported by each group. The summary reports have been assembled from the transcripts of the rapporteurs' reports to the plenary sessions and some notes taken by participants in the Working Groups.

## PARTICIPANTS IN WORKING GROUPS

| Group I | Group II | Group III |
|---|---|---|
| M. Aaston | B. Allen | L. Bohrson |
| K. Anderson | A. Banga | N. Bussieres |
| H. Cutforth | C. Chang | R. Desjardins |
| R. Divi | K. Darlington | P. Dzikowski |
| J. Dyer | F. Davies | N. Foroud |
| B. Grace | M. Dick | R. Godwin |
| M. Goebel | J. Eley | Y. Jame |
| P. Louie | R. Granger | R. Lawford |
| P. Landine | P.D. Gupta | R. Leith |
| F. Morton | A. Haugham | F. Martin |
| D. McNaughton | R. Hopkinson | H. Maathuis |
| B. Paruk | K. Johnstone | B. McConkey |
| J. Pomeroy | V. Klemes | R. Raddatz |
| S. Shewchuk | B. Latham | D. Sosulski |
| R. Street | C. Labine | H. Steppuhn |
| G. VanderKamp | E. Light | A. Vandenberg |
| E. Wheaton | L. LiPiShan | A. Wankiewicz |
| L. Wiens | N. Livingstone | J. Whiting |
| A. Warkentin | J. Maybank | |
| | K. Munawwar | |
| | W. Nicholaichuk | |
| | B. Yee | |
| | L. Warner | |

**WORKING GROUP I May 20, 1987**

**Rapporteur: Stan Shewchuk**

Question 1. What level of accuracy is needed for evaporation and evapotranspiration (ET) measurements for the following applications:

i) agriculture?

ii) water resource management?

iii) other applications?

Response. The group reported that current methods of estimating evaporation on the regional level (provinces or large drainage basins) are adequate for water resource management. Current methods are not accurate enough for local, or site-specific studies. Discussion in the group and with others indicated that some applications are much more demanding than others. In general, operational applications of evaporation in agriculture and water resources management do not require high precision (can be order of +/- 20%). Scientific work on the water balance, and predictions of the effects of land use change are much more demanding, requiring errors of less than 10%. Ground water studies seem to need errors less than 10%. In some forestry studies, the accuracy must also be rather high.

The Working Group noted that there are considerable difficulties in confirming evaporation and ET estimates. There just does not seem to be any technique that can precisely measure evaporation or evapotranspiration on any scale larger than that of the laboratory.

Question 2. What new uses will be made of evaporation and evapotranspiration estimates, and what will they demand for accuracy?

Response. Two new uses mentioned were management of forced evaporation systems for sewage treatment, and field by field management of irrigated land. Neither of these is entirely new, but with improvements in instruments and micro-computers, they will more often be done on a quantitative basis. No estimate was made of the accuracy required in evaporation estimates for these applications.

Question 3. Do present measures and estimates of evaporation and ET provide the needed accuracy?

Response. This was discussed above, under Question 1. The adequacy of present techniques is dependent on application. In general, they are accurate enough for operational management, but they could stand improvement for design work and estimating the potential effects of land-use changes. The group discussed the weaknesses of the Class A evaporation pan, which is representative only of lakes the size and depth of such a pan.

Question 4. What are the priority problems related to the measurement of evaporation and evapotranspiration which need to be addressed?

Response. The Working Group thought that some improvement is needed in the quality of the Class "A" Pan, particularly with respect to calibration.

The Working Group felt that work should be done to better define the spatial scales of sampling and precision needed in evaporation measurement.

**WORKING GROUP II May 20, 1987**

Rapporteur: Brian Yee

Question 1. How representative are evaporation pan measurements?

Response The evaporation pan does not represent anything but a tiny lake with a similar heat budget to the pan instrument itself. Differences are due mainly to differences in heat budget with the scale of the lake.

Question 2. Do we need an alternative to the evaporation pan in the standard climatological network, and if so, what?

Response The Working Group suggests that the Atmospheric Environment Service should publish evaporation estimates derived from other parameters on the basis of well-accepted formulae such as the Meyer formula. The group did not feel that there are other instrumental observations that will provide a useful alternative.

Question 3. How should evaporation be measured at automated climate stations?

Response The Working Group discussed automation of the Class A pan which has already been accomplished. It was noted that the main use of automated observation is the acquisition of consistent, continuous data at normally-manned sites without hiring 24 hours per day staff. In truly remote locations, where service is done as needed and normally spaced weeks apart, the evaporation pan or other atmometers cannot be operated and observations of temperature, wind and radiation must be substituted.

Although the Class A pan is not representative directly of any natural evaporation process, it is a known quantity and thus it should be maintained as a reference network. This has an effect on automatic station operation. With automation, it is possible to have the pan water level continuously adjusted. To match the existing record better would require scheduling a once per day water level adjustment.

Question 4. What are the priority problems related to measurement of evaporation and evapotranspiration which need to be addressed?

Response The Working Group made no recommendations.

**WORKING GROUP III May 20, 1987**

Rapporteur: Rory Leith

Question 1. Do we need direct measurement of evaporation?

Response The Working Group thought that direct measurement is needed. The Group noted that eddy correlation is one of the few direct methods of measuring evaporation on a scale that represents natural processes. Evaporation pans represent directly only the process of a water body similar in all respects to the pan (size, geometry, heat budget).

Question 2. If measurements are needed, how can we best obtain aerial measurements of evaporation and evapotranspiration?

Response The best way to extend the observations spatially is by remote sensing with air and space-borne systems.

Question 3. What are the priority problems related to the measurements of evaporation and evapotranspiration which need to be addressed?

Response Research should continue toward a robust, reliable method of measuring evaporation. Also, more work is needed to associate remote sensing data with evaporation and evapotranspiration.

Development work is needed to better understand what evapotranspiration data is and what it represents. This Working Group also recommended that more (sites) and better (quality) observation data are needed. The group also suggested that improvements are needed in our ability to estimate evaporation at low temperatures.

DISCUSSION IN PLENARY SESSION, May 20, 1987

1. Evaporation pans as standard observations.

- Not everyone wants more evaporation pans, since they do not clearly represent any natural evaporation process.
- People do evaporation pan measurements because they feel more comfortable watching real measurements of evaporation in the field.

2. Alternatives to evaporation observation data

- There are many equations for evaporation estimates, but it may be very hard to come up with universally credible constants for their application.
- There is at least one equation that does not require any local constants for its application (Morton's Complimentary Relationship Model).
- There are estimates from other weather observations that perform better in a water balance than evaporation pans.
- The water balance for a basin is the best measure of basin evaporation, but only if all the other factors can be resolved to a high precision. Typically, they cannot, because of the variability of precipitation and the unknown amount of seepage into and out of a basin.

3. Research needs

- Research needs are on a small-area scale, such as the flux over a cultivated field or a patch of forest. The focus should be on micrometeorological research and the related processes of soil percolation and plant evapotranspiration (Shewchuk, SRC).
- The wider view will have to look at general plant and soil processes (Morton).
- A water balance must be done to establish the actual evapotranspiration, so that an estimate of adequate precision can be applied to further research on other processes (Warkentin).
- There exists a demonstrated capability to measure actual evaporation, at least in a research mode.

## SESSION IV: PROCEDURES FOR CALCULATING EVAPORATION AND EVAPOTRANSPIRATION

**Chairman: Vit Klemes**

# PRACTICAL ESTIMATES OF AREAL EVAPOTRANSPIRATION

by
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Reliable estimates of actual areal evapotranspiration are essential to significant advances in the science and practice of hydrology. Direct measurements, such as those provided by lysimeters, eddy flux instrumentation and Bowen-ratio instrumentation, give point values, require constant attendance by skilled personnel and are based on unverified assumptions. A critical view of the methods used to estimate actual areal evapotranspiration has indicated that the conventional conceptual techniques, such as those used in current watershed models, are based on assumptions that are completely divorced from reality; and that causal techniques based on processes in the soil-plant-atmosphere system are not likely to prove useful for another generation. However, the complementary relationship between areal and potential evapotranspiration can do much to fill the gap until such time as the causal techniques become practicable. This is because it provides the basis for a model that permits actual areal evapotranspiration to be estimated from its effects on the routine climatological observations needed to estimate potential evapotranspiration. Furthermore, spinoff from the complementary relationship permits lake evaporation to be estimated from routine climatological observations in the land environment.

The complementary relationship models have a realistic conceptual and empirical basis and require no local calibration (or tuning) of coefficients. Therefore, they are falsifiable (i.e. they can be tested rigorously) so that errors in the associated assumptions and approximations can be detected and corrected by progressive testing over an ever-widening range of environments. Such a methodology uses the entire world as a laboratory and requires that a correction made to obtain agreement between model and water budget estimates in one environment must be appli-

cable without change in all other environments. Estimates produced by the complementary relationship areal evapotranspiration (CRAE) model agree closely with comparable water budget estimates for more than 150 river basins in North America, Africa, Ireland, Australia, New Zealand and Brazil. Furthermore, complementary relationship lake evaporation (CRLE) model estimates agree closely with comparable water budget estimates for 16 lakes in North America and 1 lake in Africa.

There have been great difficulties in making the complementary relationship understandable to the hydrological and meteorological communities. This may be because textbooks, university courses and the literature dogmatically inculcate a narrow, simplistic and untested view of hydrometeorological processes, a view which the complementary relationship exposes as false. The lack of understanding is unfortunate because the complementary relationship models have the potential to revitalize the science and practice of hydrology by providing the kind of reliable, independent inputs that are needed for detailed water balance studies; for hydrological, agricultural and fire hazard forecasts; for detecting the development of error in hydrometeorological records, for detecting and monitoring the effects of land-use changes; for predicting and monitoring the effects on the water balance of reservoir evaporation; for other better known applications; and for the further research that is needed before causal methods can be developed. The primary purpose of this presentation is to promote a better understanding of the complementary relationship.

## RECOMMENDED REFERENCES


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# ESTIMATION OF EVAPORATION AND EVAPOTRANSPIRATION METHODS USED BY AES

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Evaporation is the loss of water to the atmosphere from a free water surface. Evapotranspiration is the loss of water to the atmosphere from water, soil and plant surfaces. The Atmospheric Environment Service does not make routine measurements of these variables. Conventional methods are used to derive these variables from basic meteorological observations on request or for specific studies.

## EVAPORATION

For shallow lakes, i.e. lakes with negligible heat storage, evaporation estimates are computed using Class A evaporation pan data, the Christiansen (1966) formula or the Priestly-Taylor (1972) model. Class A pan data is corrected to provide an estimate of shallow lake evaporation by using the method described by Kohler, et al. (1955). Monthly values of these estimates for 124 stations across Canada are published routinely. The Christiansen formula is an empirical relationship for estimating pan evaporation loss from basic meteorological observations (temperature, humidity, sunshine, etc.). It has been used to provide greater spatial coverage than is available from the Class A pan network in the preparation of mean evaporation maps for Canada (Ferguson et al., 1970).

The Priestly-Taylor model has gained popularity for estimating shallow lake evaporation loss because it is a physically sound model and has a relatively simple formulation. Its main drawback is the requirement for net radiation over the water surface of interest as one of its input parameters. Measurements of this parameter are not normally available and have to be estimated. A comparison of shallow lake evaporation estimates from Class A pan data and the Priestly-Taylor model at high latitude stations is given in a study by Louie (1979).

Evaporation from deep lakes where heat storage is significant is estimated using mass transfer or energy budget techniques. The Hydrometeorology and Marine division routinely computes monthly evaporation estimates for each of the Great Lakes using the mass transfer method. The lake water surface temperatures for these computations are derived from satellite infrared data. Because the energy budget method requires special input parameters (temperature and humidity gradients, water temperature profile, net radiation), it has only been applied to a few studies by AES.

## EVAPOTRANSPIRATION

Evapotranspiration estimates are computed using conventional methods by first computing a potential evapotranspiration (PE) value and then applying a climatic water balance with an assumed soil moisture drying curve to derive the actual evapotranspiration (Johnstone and Louie, 1983). Assumed ratios of AE/PE for different cover types in conjunction with a large scale water balance have also been used to derive mean annual national maps of evapotranspiration (Hydrological Atlas of Canada, 1987).

Values of PE are computed using conventional methods which include Penman (1948) and Priestly-Taylor (1972) when radiation data is available or can adequately estimated. For most climate stations where only temperature and precipitation data are available, empirical formulae such as Thornthwaite (1948) and Baier-Robertson (1965) are used.

## BASIC DATA REQUIREMENT AND AVAILABILITY

Since direct measurements of evaporation or evapotranspiration are not routinely made nor available, they must be derived from other meteorological parameters. Table 1 shows the data requirements for the various models for computing evaporation and evapotranspiration. Table 2 shows the current network data available for input into these models.

TABLE 1. DATA REQUIREMENTS FOR EVAPORATION/EVAPOTRANSPIRATION ESTIMATES

| Method | Meteorological Parameters | Other Parameters | Minimum Network |
|---|---|---|---|
| Lake Evap | $E_p$, T, $T_w$, W | Z | Class A Pan |
| Mass Transfer | T, RH, W | $T_s$ | Synop/Hourly |
| Energy Budget | T, RH, $R_n$ | Q, G | Special |
| Priestly-Taylor | T, $R_n$ | G | Synop/Hourly |
| Penman | T, RH, W, $R_n$ | G | Synop/Hourly |
| Morton | T, $T_d$, $R_s$ | | Synop/Hourly |
| Empirical | T, P | Lat, WHC | Climat T&P |

$E_p$ = pan loss
W = wind
$R_n$ = net radiation
$T_d$ = dew pt temp
Lat = stn latitude

T = air temp
$R_H$ = rel. humidity
Q = heat storage
$R_s$ = solar rad
WHC = soil water holding capacity

$T_w$ = pan water temp
$T_s$ = water sfc temp
G = ground heat flux
P = precipitation
Z = stn elevation

TABLE 2. NETWORK DATA AVAILABILITY

| Network | Parameters used for Evap/ET | Total Stations | Total Active Stations | Active with 30+ Yrs Record |
|---|---|---|---|---|
| Class A Pan | $E_p$, $T_w$, W | 237 | 124 | 36 |
| Net Radiation | $R_n$ | 32 | 23 | 5 |
| Solar Radiation | $R_s$ | 74 | 49 | 21 |
| Sunshine | S | 589 | 307 | 134 |
| Synoptic | T, $T_x$, $T_n$, $T_d$ W, P, atm press, cloud amount | 740 | 214 | 155 |
| Hourly | T, RH, W atmos. press, cloud amount | 528 | 321 | 125 |
| Climate | T, P | 5443 | 2133 | 989 |

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# THE CONCEPT OF POTENTIAL EVAPOTRANSPIRATION AND ITS USE IN A WINDY SEMI-ARID ENVIRONMENT IN SOUTHERN ALBERTA

By
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Many of the simulation models currently in use in Alberta accumulate potential evapotranspiration (PE) totals to estimate the total evaporation from a site during a given period of time. This information is then used to make management decisions. Eight different, commonly used methods of calculating PE were compared under different weather conditions at the Agriculture Canada Research Station in Lethbridge, Alta. Under conditions of low wind speed and moderate humidity the methods produced similar results. However, under dry windy conditions estimates of PE differed widely. The accumulated PE for the 21 days examined here ranged from a low of 75.0 mm as calculated with the Jensen-Haise method to a high of 138.1 mm with the Doorenbos-Pruitt formula for adjusted pan evaporation. Discrepancies this large could have serious consequences for such applications as irrigation scheduling.

An estimate of potential evaporation is often used as the driving function for much larger simulation models in hydrological studies, crop-yield predictions, irrigation scheduling and soil moisture evaluation. The effect of PE estimates on two soil moisture simulation models, the soil-plant-atmosphere-water model (SPAW) of Saxton et al. (1974) and the diffusion-based soil water model (DBSW) of Hayhoe and DeJong (1982) demonstrated that simulation models often have specific requirements for the type of PE estimate. Such models are most sensitive to variations in PE estimates when surfaces are wet and actual evaporation and evapotranspiration approach PE values.

Some of the computer simulation models currently in use on an operational basis in the semi-arid windy environment of Southern Alberta may be considerably underestimating evaporation by employing equations that do not account for advective energy input. PE equations that require wind and especially humidity data more correctly simulate real conditions in the chinook-dominated climate of Southern Alberta.

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# EVAPORATION FROM DRIFTING SNOW

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Erosion of surface snow, its transport by the wind and subsequent deposition are familiar phenomena to residents of the Prairie Provinces. Evaporation from snow during drifting is a less well known phenomenon which can result in major losses from the snowcover of cold, semi-arid and windswept landscapes such as the Canadian Prairies and Arctic. Evaporation occurs in the form of sublimation from the ice surface of blowing snow particles to atmospheric water vapour. The rate of sublimation is controlled by the radiative, latent and sensible energy fluxes to the blowing snow particle. Meteorological factors affecting this energy balance are; solar radiation incident on the particle, windspeed relative to the particle and the ambient atmospheric temperature and water vapour pressure. Where wind directions and weather conditions vary widely from blizzard to blizzard, it is felt that a physically based model of snow transport quantities and sublimation rates is necessary to accurately determine the quantities of surface snow which sublimate before re-deposition. Advantages of a physically based model include its versatility in application to unique environments and problems and the ease of upgrading such a model as the results of research become available.

This presentation discusses:

1) The results of field measurements of vertical gradients of atmospheric snow density, wind speeds, temperature and humidity during blowing snow;
2) The results of a physically based model of sublimation from blowing snow for various meteorological conditions.

Over one winter near Saskatoon and two near Loreburn, Saskatchewan the mean vertical gradients of windspeed, air temperature, dewpoint, snow particle concentration and drift density (mass concentration of blowing snow) were measured at 6 levels, at heights from the snow surface to 3m. Despite strong mechanical mixing during blowing snow, there is a tendency for stable temperature gradients compared to antecedent conditions. When temperatures at the 2m level are near freezing, temperature gradients of $2^{o}C$ per metre can develop. Relative humidity decreases with increasing height during blowing snow from a maximum near the 20cm level.

Differences in relative humidity of 20% can develop between the 2m level and the surface layer (< 0.2m) during a strong blizzard in "warm" weather. These measurements indicate strong fluxes of water vapour upward from and heat downward to the dense lower layers of drifting snow.

A mathematical model has been developed which calculates the sublimation from a column of blowing snow. Flow through the column can be developing horizontally from a boundary or be fully developed as in the centre of a field. Blowing snow transport rates through the column are calculated using a two-phase flow energy balance on the mean flow near the surface and turbulent transfer relationships for flow at levels greater than 2cm above the surface. The model considers temperature and solar radiation levels and vertical gradients of particle size, drift density, turbulence, water vapour pressure and temperature within the column. For constant conditions, variation of the solar radiation from a flux typical at noon on a clear April day at 3000m elevation to nighttime values changes the resulting sublimation rate no more than 3%. However, an increase in air temperature from -35$^{o}$C to -1$^{o}$C results in a 22-fold increase in sublimation rates. At -15$^{o}$C a decrease in humidity from 90% to 40% RH results in a 6-fold increase in sublimation rates. The drift density and therefore sublimation rate increases approximately as the square of the windspeed. Dramatic losses of moisture can occur in strong blizzards, with surface snow water equivalent losses to sublimation and vertical transport of 10.4 mm/day for a 10 m windspeed of 20 m/s temperature of -1$^{o}$C and RH of 70%.

The following table lists horizontal and vertical transport and sublimation rates for a 10 m column of blowing snow. Calculated from these values are the distance over which blowing snow will be completely replaced and the snowcover water equivalent required to replace snow lost by sublimation within the column and by vertical transport out of the column. Constant conditions assumed for these estimates are a meteorological fetch greater than 300 m, windspeed at 10 m of 12 m/s and a fresh, deep snow layer overlying older snow (windspeed at the threshold of blowing $u_{10}$ = 4.5 m/s). It can be seen that sublimation affects the transport distance of blowing snow and overwinter losses of snowcover, however the magnitudes change dramatically with meteorological conditions. The potential errors in assuming a constant blowing snow sublimation rate in any hydrologic design are evident from the variation in $D_R$.

The calculation procedure used to calculate these estimates is in the final stages of compilation as an operational model by the Division of Hydrology. The model uses standard hourly AES. data available from stations which record the occurrence of "blowing snow". Meteorological conditions measured at AES. stations are transformed to estimate those conditions over particular agricultural snow surface geometries. This allows estimation of the potential effects of land use and engineering structures on the transport and sublimation quantities of blowing snow. It is hoped that accurate estimates of over-winter sublimation losses from and redistribution of the snowpack will permit water and agricultural resource managers to make informed decisions regarding snowcover quantities available for snowmelt in the spring.

RESULTS OF DIVISION OF HYDROLOGY BLOWING SNOW MODEL

| T | H | Q* | $Q_{BS}$ | $Q_V$ | $Q_{SB}$ | $D_S$ | $D_R$ | E |
|---|---|---|---|---|---|---|---|---|
| -15 | 70 | 120 | 74.4 | 8.4 | 4.8 | 15.5 | 5.6 | 1.14 |
| -15 | 70 | 1115 | 74.4 | 8.4 | 4.9 | 15.2 | 5.6 | 1.15 |
| -15 | 90 | 120 | 74.4 | 8.4 | 1.6 | 46.5 | 7.4 | .86 |
| -15 | 40 | 120 | 74.4 | 8.4 | 9.7 | 7.7 | 4.1 | 1.56 |
| -35 | 70 | 120 | 80.6 | 9.1 | 0.7 | 115.1 | 8.2 | 0.85 |
| -01 | 70 | 120 | 70.6 | 7.9 | 15.4 | 4.6 | 3.0 | 2.0 |

SYMBOLS:

T = 2m air temperature ($^{O}C$)
H = 2m relative humidity (percent)
Q* = incoming solar radiation ($J/(m^2s)$)
$Q_{BS}$ = horizontal blowing snow flux to 2m height ($g/(m\ s)$)
$Q_{SV}$ = sublimation rate of blowing snow below 10m height ($mg/(m^2s)$)
$Q_V$ = vertical blowing snow flux at 10m height ($mg/(m^2s)$)
$D_S$ = distance over which sublimation will require complete replacement of blowing snow below 10m (km)
$D_R$ = distance over which sublimation and vertical transport will require complete replacement of blowing snow (km)
E = SWE. erosion rate for fully developed flow (mm/day)

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# APPROPRIATE PARAMETERS FOR USE IN THE MEYER FORMULA

by
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## INTRODUCTION AND CONTEXT

An important aspect of any surface water supply analysis is the determination of potential gross evaporation from a free water surface. The evaporation loss from a reservoir or water supply system is usually quite significant and has a major impact on the water supply potential. The ability to provide a realistic estimate of this component can have direct implications on the feasibility and operation of a water supply system. Various methods have been used to estimate potential gross evaporation. However, the method that is discussed herein is the one currently used by the Prairie Farm Rehabilitation Administration (PFRA) based on the Meyer Formula.

The Meyer Formula was initially proposed by A.F. Meyer (1915) and subsequent clarified (Meyer, 1942). McKay and Stichling (1961) studied several methods of estimating gross evaporation were compared with water balance calculations for Weyburn Reservoir. The resulting report contained a conclusion which stated that the Meyer Formula, as described in the 1942 report, was the most suitable method available at that time because it was the most practical and provided the most reasonable estimates of monthly gross evaporation.

Consequently, the Saskatchewan-Nelson Basin Board (SNBB) calculated monthly gross evaporation, using the Meyer Formula as described in the 1972 SNBB report (SNBB, 1972), for 14 locations across the prairies for the period 1911-67.The results are presented in Prairie Provinces Water Board Report No. 5 (PPWB, 1952). S.J. Buckler (1973) again recommended the use of the Meyer Formula for the calculation of gross evaporation but with some stipulation regarding the coefficient.

In 1973, PFRA began updating estimates of gross evaporation made by the SNBB for the 14 locations in the prairie region and distributing this data to various agencies, consultants, universities and interested individuals. However, it soon became

apparent that the gross evaporation estimates were being significantly affected by one or more factors. Recently, a study was initiated to identify these factors and to make the appropriate adjustments. The finds of this study are briefly discussed in this paper.

## DESCRIPTION AND FINDINGS

The Meyer Formula is:

$$E = C(Vw - Va)(1 + 0.1W)(1 + 0.00001\,A)$$

where: E = monthly evaporation in inches
C = Meyer Coefficient
Vw = saturation vapor pressure in inches of Hg corresponding to the mean temperature of the water surface
Va = actual vapor pressure in inches of Hg in the air at 25 feet above the water surface
W = wind speed in mph at 25 feet above the water surface
A = elevation of water surface above mean sea level in feet

As the recorded data was not obtained at the appropriate datum, the basic data had to be adjusted (e.g. actual vapor pressure, wind speed) or calculated (e.g. water temperature) before gross evaporation could be estimated using the Meyer Formula. The procedures that have been used to date for determining the various components of the Meyer Formula are described in the SNBB (1972) report.

The gross evaporation estimates indicated relatively large annual values for the last 30 years as illustrated in Figure 1. Similar patterns were observed for all of the other 13 locations.

Six factors which may have contributed to the observed phenomenon were identified. They are:

1. improved data quality,
2. inconsistent data base,
3. anemometer height adjustment,
4. variation of Meyer coefficient,
5. determination of water temperature, and
6. climate change.

Although all of these factors may have had some influence on the estimates of gross evaporation, the major impact was attributed to an inappropriate adjustment for anemometer height and inconsistent data base. The effect of adjusting the procedure and the data base to correct these two factors is illustrated in Figure 1.

## CONCLUSIONS

Significant improvements can be made in the estimation of potential gross evaporation using the Meyer Formula if the appropriate adjustment procedures and data are used. As illustrated by the example presented in Figure 1, the annual gross evaporation estimates become more homogeneous when proper procedures and data are used. The effects of other identified factors appear to the relatively insignificant on an annual basis. However, the effect of some factors (e.g. water temperature) may be significant in the estimation of monthly gross evaporation.

## IMPLICATIONS FOR FURTHER RESEARCH

With respect to the Meyer Formula, more research and/or analysis of existing data could be undertaken to:

1. reassess the relationship between air temperature and water temperature, and
2. determine a relationship between Meyer's coefficient and the size of a water body.

With respect to the determination of gross evaporation, more work could be done to compare the various methods that are currently available for estimating gross evaporation. However, in order to assess the various methods, estimated values derived from each method must be compared to a standard. Unfortunately, the availability of good quality data for use in a water budget (the standard by which all methods are usually judged) is limited.

At present, PFRA is revising the estimates of potential gross evaporation that have been obtained using the Meyer Formula by correcting obvious flaws in the methodology. The revised estimates will be distributed to interested parties for subsequent use in analyses requiring gross evaporation estimates.

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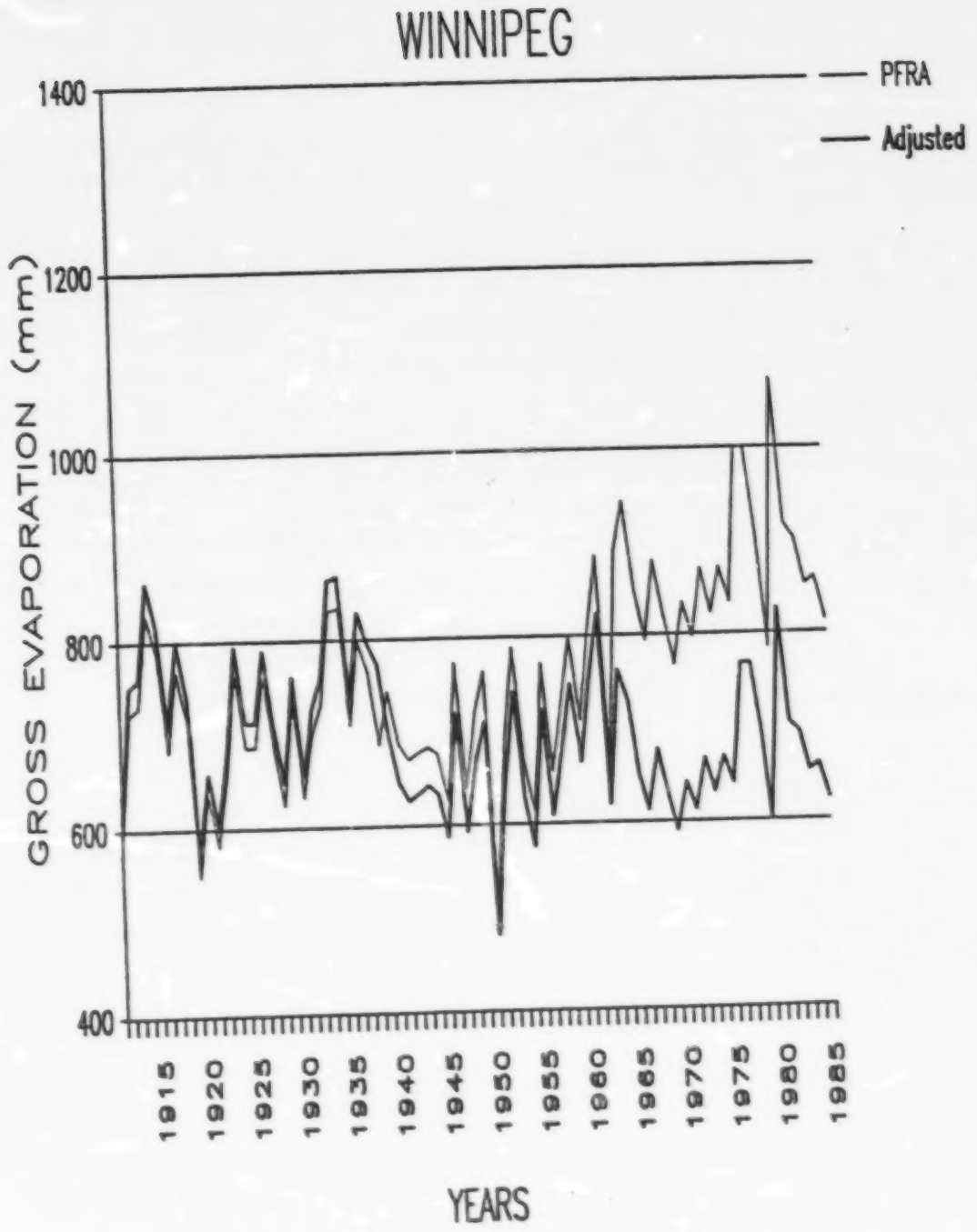
WINNIPEG
PFRA
Adjusted
1400
1200
1000
800
600
400
GROSS EVAPORATION (mm)
1915
1920
1925
1930
1935
1940
1945
1950
1955
1960
1965
1970
1975
1980
1985
YEARS

# A MODIFIED FORM OF THE JENSEN-HAISE EQUATION FOR POTENTIAL EVAPOTRANSPIRATION FOR USE IN SOUTHERN ALBERTA

By
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Evapotranspiration (ET) is frequently estimated from potential evapotranspiration (ETP). The accuracy of this estimate depends on how accurately the ETP is computed. ETP is generally computed by one of several equations based on meteorological data. The selection of the equations seems to be based on the individual's preference and the availability of the required weather data and parameters. The Jensen-Haise equation, one of the most commonly used equations in southern Alberta, requires daily maximum and minimum temperatures, solar radiation, and two coefficients derived from the mean elevation and saturated vapor pressure data. It does not include the wind variable, a dominant weather factor in evaporation in this region. The growing conditions in southern Alberta are affected strongly by the Chinook wind, a warm and dry wind that sweeps down the eastern slopes of the Rocky Mountains.

No single method to estimate ETP from meteorological data is satisfactory for all climatic regions without some local or regional modifications. Equations of ETP generally perform well under the climatic conditions where they were originally developed, but poorly for other sites with different climates. Under such conditions further investigation is required to determine which climatic variables, not already used, could be incorporated to improve estimates of ETP. In some areas with high evaporation, the energy used in ET may exceed the energy of net radiation. Hot-dry winds blowing over top soil and crop surfaces often account for the excess energy used for evapotranspiration. If such wind variable is ignored, the ETP is obviously underestimated.

Past field studies have indicated that the Jensen-Haise equation underestimates ETP for southern Alberta weather conditions. A multiple regression equation has been developed to modify the equation by taking into account the wind variable using 166 days of 1986 daily temperature, radiation, Class-A Pan evaporation, and wind data. The modified equation was incorporated in a digital computer model for

irrigation management, which estimates the actual ET of a crop from the ETP, and the a daily soil moisture value based on a crop coefficient curve, maximum soil-available moisture, allowable depletion, rainfall, and irrigation data. The estimated soil moisture compared sufficiently well with measured soil moisture data obtained by the gravimetric method during the 1986 growing season. More tests are planned for the 1987 growing season to verify the validity of the equation.

## REFERENCE

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## SUMMARY OF DISCUSSIONS IN SESSION IV, May 20, 1987

1. CRAE Model Fred Morton

Q. Why are the intervals for estimating evapotranspiration five days and one month?

A. One month is a convenient climatologic interval. Five days is a minimum interval for use in mid-latitudes where the air mass can change for one to a few days at a time.

Q. How is potential evaporation defined for this model?

A. It is the evaporation that would occur from an isolated evaporation pan in a dry place. Evaporation uses solar radiation plus advected heat. The less evaporation taking place in the surrounding area, the more evaporation from the small lake or trial pan.

Q. You have mentioned that in the Cameroons, the Potential Evapotranspiration was reduced due to the increased amount of actual evapotranspiration which increased the humidity. Is the real source of moisture causing high dew points, an ocean somewhere?

A. The high humidity does come from an ocean, but it is by way of the local soil.

Q. Is it by way of the soil or by air mass change?

A. That question implies that there is a long transition zone for the air to come into equilibrium. Observations have shown that equilibrium develops over a very short distance, of the order of 100m.

2. Potential Evapotranspiration estimators B. Grace

Q. Are the models you have presented [for estimating evapotranspiration in a windy environment] useable in practical agricultural applications?

A. The presentation is based on work at a well-instrumented site (Lethbridge), with adequate data to run various wind-effect models. It is realized that these cannot be used at all locations.

Comment: deJong discusses all these models in the latest issue of Agricultural Engineering.

3. Long-term trends by the Meyer Formula Fred Martin

Q. (i)Why are the corrections on your trend lines more significant in recent years than in early years?

(ii)People in Ducks Unlimited are interested in showing that your graphs reflect the consequences of land use changes. Do you have any comment?

A. (i) The main correction is for anemometer height. The anemometers were typically at 90 feet in early years and all years have been adjusted to a standard height of 25 feet.

(ii) Some agencies imply things from data that were not intended to be shown.

4. Evaporation of Snow J. Pomeroy

Q. Do you assume the vapour pressure over snow surfaces is only 6.1mb?

A. We assume the snow particle cools off to the ice bulb or wet bulb temperature. The vapour pressure goes to the saturation pressure over ice at the surface of the particle [immediately at the surface], and there is a gradient to the ambient value.

Q. Does your model have any sort of energy balance for the snow particles? It seems that 4mm/day of evaporation requires 100W per square metre, which is more than you get on a winter day.

A. The evaporation removes heat from the air and causes a severe temperature depression in the drifting snow layer. For example, during drifting snow in January with wind 15km/hr, the air temperature at 2m was +2 deg. C and at 20cm it was -2°C. It is difficult to do an energy balance for the drifting snow layer of air due to turbulence effects, which cause much vertical advection.

Comment: The Katabatic winds off some ice-fields in Antarctica have been found to be self-sustaining on the basis that the sublimation of the drifting snow contained in this wind cools the air and it thus flows down the slope. Japanese and Alaskan scientists have both reported this phenomenon to last for days.

## SESSION V: CASE STUDIES OF EVAPORATION AND EVAPOTRANSPIRATION ESTIMATES.

**Chairman - Bruce Godwin, Prairie Provinces Water Board**

# FIELD TESTING THE COMPLEMENTARY RELATIONSHIP AREAL EVAPOTRANSPIRATION (CRAE) MODEL

by

*1. W. Nicholaichuk, S. Fogarasi, 2. C. Chang, G. Beke,
3. F. Davies, 4. F. Morton, 5. J. Whiting

A complementary relationship areal evapotranspiration (CRAE) model has been found to provide reliable independent estimates of actual areal evapotranspiration in most parts of the world with no locally tuned coefficients (Morton, 1983). However the potential application of the CRAE model to estimate the effect of different land use on evapotranspiration has not been examined. To this end, a cooperative field study with Agriculture Canada, Alberta Environment, Saskatchewan Research Council and Environment Canada was conducted in 1986 to evaluate the CRAE under various land use conditions.

Sites representing three soil moisture and land use conditions (irrigated cereal, natural grassland and a dryland cereal) were selected in Southern Alberta. Replicated sites, with a 300 meter fetch were instrumented to provide continuous independent measurements of humidity, dewpoint and air temperatures, sunshine, precipitation and soil moisture using the gamma probe during the growing season. The instrumentation constructed and used for this study is described.

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Data collected was used to calculate evapotranspiration using the CRAE model. Calculated evapotranspiration estimates were compared to the results of a water balance for each of the sites assuming that evapotranspiration was equal to precipitation plus a change in soil moisture storage. It was assumed that soil water drainage was negligible. Based on one years' results, the following are noted:

1. Evapotranspiration as determined by the model was less than the observed (i.e. precipitation + changes in soil moisture) by as much as 33%. The model tended to underestimate evapotranspiration under irrigated conditions more than under cultivated dryland or pasture conditions. An examination of soil moisture profiles suggested measurements to a depth of 1.4 meters were insufficient. Soil moisture measurements should have been taken to a depth where soil moisture changes are negligible. As a result, changes in soil moisture storage to only a depth of 1.4 m during the growing season may be a major source of error, particularly under irrigated conditions.
2. A comparison of mass curves for each site suggests that topography may have an influence on evapotranspiration. Evapotranspiration tended to be higher at elevated sites compared to lower slope positions. Furthermore, the mass curves do suggest that relative evapotranspiration rates for each land treatment were as expected (i.e. irrigated ET was greater than dryland cereal and dryland pasture).
3. Further study is required to determine the sensitivity of the model to sources of error. For example, to what extent does an incremental change in dew point temperature affect evapotranspiration, etc.
4. A systematic evaluation of all sources of error is required. Namely: the spatial variability in soil moisture changes; accuracy of dewpoint measurements (i.e. verification of dewpoint temperatures using humidity measurements and humidity as determined by humicells).

In conclusion, based on one years' results, the application of the CRAE model to evaluate the effect of land use on evapotranspiration are encouraging. Further study is required to accurately evaluate the potential application of the model.

## REFERENCE

Morton, F.I., 1983. Operational estimates of areal evapotranspiration and their significance to the science and practice of hydrology. J. Hydrology, 66:1-76.

# OVERVIEW OF APPLICATIONS OF EVAPORATION ESTIMATES IN RESERVOIR SIMULATION AND OPTIMIZATION MODELS

by
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One of the main operating goals of a hydro-thermal power system is to supply electricity to the customer as economically as possible. Since the operating costs of hydro plants are generally very small compared to those of the thermal plants that burn coal or gas for power production, the total cost of generating electric power in a hydro-thermal system could be reduced by using more efficiently the available hydro generating facilities.

An heirarchical approach is presented here for optimal scheduling of multi-purpose (i.e. flood control, irrigation, recreation, hydro power, fisheries, etc.) multi reservoir systems.

The approach primarily consists of solving the long-term (2-20 years), mid-term (1 season - 1 year) and short-term (1 week - 1 month) reservoir scheduling problem through a set of simulation and optimization models. These models take into account complexities such as multiple objectives, system nonlinearities, trade-off of water usage for maximizing immediate benefits vs. future benefits and numerous design, as well as operational constraints (e.g. lower and upper bounds on reservoir levels and discharges). In addition to other inputs, these models require estimates of net evaporation for all major reservoirs in the system under natural conditions. These simulations and reservoir optimization models could be employed to investigate the effects of uncertainties in the estimation of net evaporation rates on the water availability for other uses. As an example, the operation of three reservoirs (i.e. Lake Diefenbaker, Codette and Tobin Lake) and associated hydro plants on the Saskatchewan River system was optimized over a one-year period for the two cases of error (i.e. +/-50%) in the initial estimation of net evaporation rates for Lake Diefenbaker. For the above cases studied, the test results show that the hydro power production from the three plants is significantly affected (to a tune of approximately +/-90 GW.h).

## SENSITIVITY OF HYDRO PRODUCTION WRT VARIATIONS IN NET EVAPORATION

| | | HYDRO ENERGIES (GWH) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | COTEAU CREEK | | | NIPAWIN | | | SQUAW RAPIDS | | | TOTAL | | |
| Month | Ave. Net Evaporation (m3/s) | Low Evap | Ave Evap | High Evap | Low Evap | Ave Evap | High Evap | Low Evap | Ave Evap | High Evap | Low Evap | Ave Evap | High Evap |
| Jan | 0 | 122 | 120 | 111 | 113 | 111 | 104 | 115 | 113 | 109 | 350 | 344 | 324 |
| Feb | 0 | 95 | 101 | 85 | 94 | 99 | 86 | 74 | 76 | 68 | 263 | 276 | 239 |
| Mar | 0 | 30 | 26 | 30 | 51 | 49 | 50 | 41 | 41 | 40 | 122 | 116 | 120 |
| Apr | 11 | 20 | 19 | 20 | 80 | 79 | 80 | 43 | 43 | 44 | 143 | 141 | 144 |
| May | 41 | 42 | 42 | 42 | 106 | 106 | 106 | 92 | 92 | 92 | 240 | 240 | 240 |
| Jun | 58 | 31 | 31 | 31 | 116 | 116 | 116 | 105 | 104 | 105 | 252 | 251 | 252 |
| Jul | 86 | 91 | 55 | 47 | 162 | 141 | 136 | 139 | 124 | 119 | 392 | 320 | 302 |
| Aug | 22 | 62 | 61 | 55 | 109 | 108 | 105 | 92 | 95 | 90 | 263 | 264 | 250 |
| Sep | 14 | 50 | 52 | 55 | 80 | 81 | 82 | 70 | 71 | 70 | 200 | 204 | 207 |
| Oct | 10 | 80 | 71 | 85 | 86 | 81 | 90 | 75 | 71 | 82 | 241 | 223 | 257 |
| Nov | 7 | 113 | 105 | 88 | 97 | 93 | 83 | 85 | 96 | 74 | 295 | 294 | 245 |
| Dec | 0 | 101 | 112 | 106 | 95 | 99 | 95 | 81 | 64 | 74 | 277 | 275 | 275 |
| Annual Total Plant Energy (GWH) | | 837 | 795 | 755 | 1189 | 1163 | 1133 | 1012 | 990 | 967 | 3038 | 2948 | 2855 |

Note: Low evap is 50% of average evaporation
High evap is 150% of average evaporation

# IMPROVED IRRIGATION MANAGEMENT

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Increasingly, Saskatchewan farmers are tapping into rivers as a water supply for cropping. Irrigation in Saskatchewan has many benefits. Some crops can only be grown under irrigation, and sandy soils are much more productive under irrigation. Irrigation eliminates the hazards of drought.

Some farmers treat irrigation as an insurance policy rather than as an operational system. Unfortunately, this results in much less than full benefit, and does not fully justify the high cost of installing irrigation equipment (on-farm investment of $750 to $1,000/ha for a central pivot system). The farmer's concern centres on immediate operating costs.

With normal rainfall, irrigation is required (near Outlook) on wheat for 950 hours, on corn for 1000 hours and on alfalfa for 1200 hours. Actual utilization in a normal year (1983) averaged 583 hours for all crops, and in a dry year (1984) it averaged 1004 hours.

A typical irrigation sprinkler system provides about 6mm of water per day. An extra 25 to 50mm of water will make a big difference to a crop, but will take several days of pumping to put it on.

The relationship between soil and water controls plant growth. An understanding of water behaviour in soil is necessary to good irrigation management. Gravity moves water downward, particularly in coarse-textured soil. Cohesion and adhesion slow soil moisture movements in fine-textured soils. Stratified soils of differing texture result in uneven downward or upward propogation of soil moisture. This can result in an underlying sandy layer receiving little moisture through a clayey layer, or an underlying clay layer impeding drainage from a sandy layer.

The rate of infiltration varies considerably with soil texture. Sandy soils are convenient for irrigation because infiltration from the surface to the root system is fast and even. Clay soils are more suitable for natural showery precipitation because they provide more soil moisture storage in the root zone of crops.

Soil moisture is monitored by several techniques in operations and research. The standard method used in research is the gravimetric one of weighing samples before and after drying. In soil instruments for soil moisture include the neutron probe and the soil moisture (conductivity block). Mechanical tensiometers simulate the suction of plant-roots to measure availability of moisture to plants. In operations, soil moisture is often assessed manually by qualitative differences in mechanical soil behaviour between the main moisture conditions.

The Irrigation Division of Saskatchewan Water Corporation has demonstrated increased wetting front penetration during the early part of the season. The wetting front refers to the penetration downward from the surface of the damp soil in which all the soil moisture and nutrient uptake occurs. A deeper wetting front results in a greater safety margin in case of irrigation equipment failure, and a much reduced risk of moisture stress during the final stages of filling the seeds and maturing the crop. With normal Saskatchewan irrigation equipment, wetting front penetration to 60cm deep is only possible through continuous irrigation during the relatively rainy period of late June and early July.

# LAKE EVAPORATION ON THE PRAIRIES; AN OVERVIEW

by
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## INTRODUCTION

In support of interprovincial apportionment, AES has operated a number of field projects designed to improve evaporation estimates from major prairie reservoirs. This paper describes the approach taken and discusses specific results.

## METHODOLOGY

McKay (1962) evaluated a number of methods which could be used to calculate lake evaporation. It was his conclusion that bulk aerodynamic equations could be applied with fair accuracy provided surface water temperature of a lake or reservoir is measured. Ideally the meteorological data required (humidity and wind speed) should be measured over the lake.

There are many such equations but the one developed by Meyer (1915, 1942) has been used widely on the prairies:

$$E = C_1 \times C_2 (1 + .0621\ U) (e_w - e_a)$$

where:
- $E$ = monthly evaporation (mm)
- $C_1$ = Meyer Constant - a function of humidity calculation and the nature of a water body
- $C_2$ = units conversion from English to metric units
- $U$ = wind speed (km/h) adjusted to 7.6 m above the lake surface
- $e_w$ = saturation vapour pressure (mb) corresponding to the surface water temperature
- $e_a$ = atmospheric vapour pressures (mb) adjusted to 7.6 m above the lake surface

All the input parameters are monthly averages. The use of monthly averages can introduce a biased result because the products of the fluctuations around the mean may not cancel.

## CASE STUDIES

Projects are managed at Tobin Lake, Lake Diefenbaker, Waterton reservoir and St. Mary reservoir. In all cases water temperature is measured at one or more points and most cases meteorological data are supplied from the closest weather station or stations. Attempts to measure humidity and wind on-site have been of doubtful value and greatly increased the manual data processing using conventional recording techniques. The use of data loggers could offset the latter problem but lack of security of unattended equipment would remain.

The longest existing project is at Lake Diefenbaker (see Figure) where evaporation has been calculated from 1972 for the open water season. The seasonal evaporation has a mean of 863 mm. In terms of volume, the average gross evaporation is 343,000 $dam^3$, a significant quantity of water but representing less than 4% of the average inflow to the reservoir.

On Gleniffer Lake (Dickson Dam) on the Red Deer River, Morton's lake evaporation model is applied in conjunction with on-site precipitation data to calculate net evaporation.

An unoffical monitoring program involved Moosomin reservoir on Pipestone Creek. In 1984, an attempt to apply pan derived shallow lake evaporation to this reservoir in natural flow calculations led to unbelievable results. This highlights the emerging requirement for better evaporation estimates for reservoirs on small streams in dry years.

## CONCLUSIONS

1) By measuring surface water temperature at a reservoir and using meteorological data from a nearby weather station, it is possible to provide an estimate of evaporation (employing a bulk aerodynamic equation) which more accurately depicts the season distribution and variation of lake evaporation. However in absolute terms, the resultant estimate could be biased by +/-20% due to a lack of calibration on the prairies. Reservoir specific water temperature data are required for any method which attempts to deal with the dynamic nature of the energy budget of such a water body.
2) Water temperature measured at a point may not represent the lake as a whole.
3) Estimating surface water temperature from readily available meteorological data for use in Meyer-type equations can lead to large errors in the computed evaporation even when regression equations are developed for a specific reservoir.
4) On-site monitoring is expensive in time and resources compared to the refinement which is achieved in relation to the streamflow volume. The vandal raises cost through loss of data and equipment.
5) On-site precipitation measurements would improve net evaporation calculations for apportionment in a cost effective manner. Perhaps the collection of this data should be a condition of license for reservoir operation.
6) Errors in evaporation calculations are much more significant on small streams in dry years when evaporation is comparable to streamflow.

## IMPLICATIONS FOR FURTHER RESEARCH

1) A definitive water budget study is required to properly calibrate the Meyer coefficient to prairie conditions and to assess alternative methods (e.g. Morton Lake Evaporation Model).
2) Better instrumentation (cheap but durable) for water temperature, humidity and wind with on-site processing and telemetry would reduce the data handling and provide better quality data than "nearby" measurements. Security of equipment must be improved. Monitoring of these parameters should be a part of the operating cost of a reservoir.
3) Remote sensing from satellite of surface water temperature may be possible for large reservoirs if the resolution of IR sensors on meteorological satellites can be improved. Current resolution makes this possible only for very large lakes such as Lake Winnipeg

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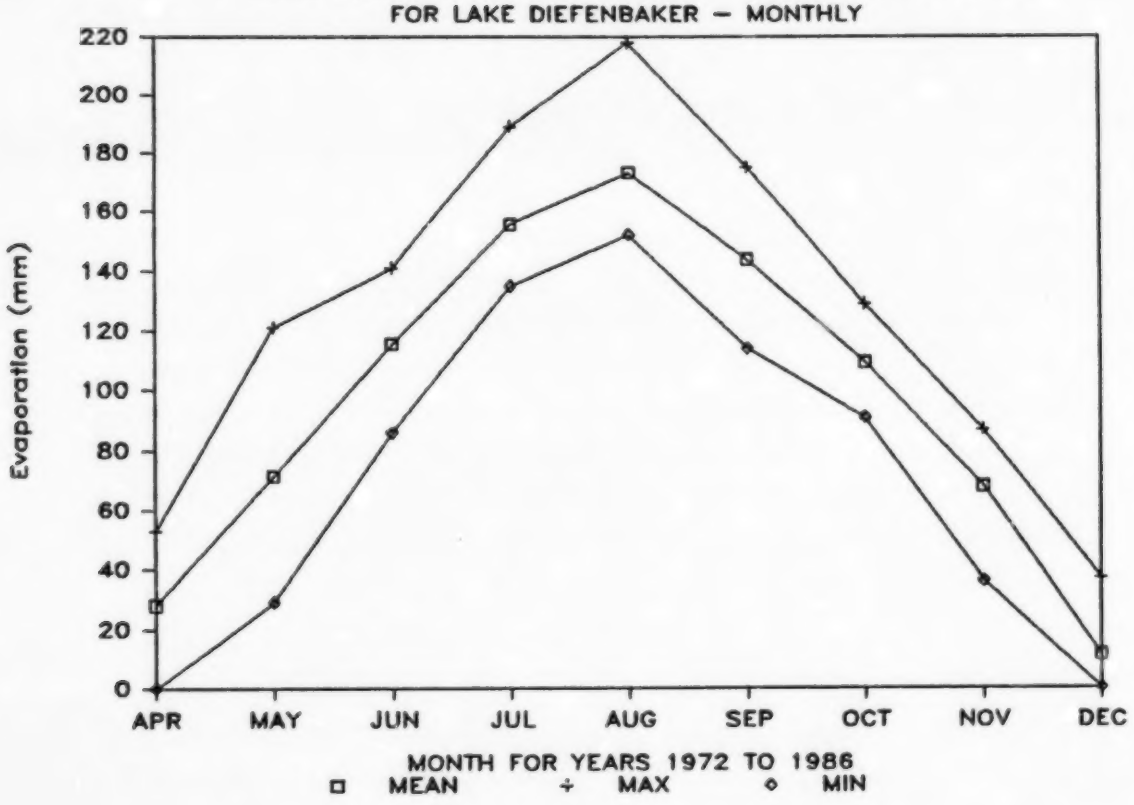
Meyer, A.F., 1915. Computing runoff from rainfall and other physical data. Paper 1348 presented at meeting of the American Soc. of Civil Engineers, April 21, 1915.

Meyer, A.F., 1942. Evaporation from lakes and reservoirs. Minnesota Resources Commission, St. Paul, Minnesota, June, 1942.

# FIGURE: GROSS EVAPORATION



# GROUNDWATER HYDROGRAPHS AND EVAPOTRANSPIRATION ESTIMATES

By
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The Saskatchewan Research Council has constructed and operates a network of 49 continuously recording groundwater wells, located throughout northern Saskatchewan. Approximately 20 years of records are available for most of these wells. The wells are completed in both shallow and deep aquifers.

Water levels in the shallow aquifers (confined by less than 30 m of glacial till and clay) exhibit a clear annual response to recharge water from the ground surface, occurring mostly in spring, and to evaporation losses during summer. However, this response cannot be easily quantified in terms of water balance, due to the complexity of the storage processes within the capillary fringe. (It is often overlooked that changes of groundwater storage do not occur at the water table but above the water table within the capillary fringe).

The deep aquifers (confined by more than 30 m of clay and glacial till) exhibit regular annual fluctuations of water level, superimposed on longer-term changes. Their annual cycles consist of a gradual rise from about September to May, and a more rapid fall between May and September. The total yearly change is usually about 50 to 150 mm.

Data gathered in recent years show clearly that the deep aquifers are isolated from the effect of annual water-table changes, because the thick glacial tills have very low permeability. It is becoming clear that the regular annual fluctuations are a direct loading effect and reflect the total annual change of moisture above the aquifer, including water-table storage, soil moisture, ponded water and snow. The annual fluctuations show a reasonably close correlation, both in timing and magnitude, with total basin storage calculated using Morton's areal evaporation model. One might say therefore that the deep aquifers act as giant but inexact lysimeters.

## REFERENCES

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van der Kamp, G. and J.E. Gale, 1983. Theory of earth tide and barometric effects in porous formations with compressible grains. Water Resources Research 19:538-544.

# EVAPORATION AND TAILINGS PONDS IN THE N.W.T.

by
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## BACKGROUND

Under the mandate of the Northern Inland Waters Act, the Water Resources Division of Northern Affairs regulates water use in the NWT. Through the Water Board, all water uses over about 200 $m^3$/day and all liquid waste discharges are licensed. Of the licensed users, fifteen are mines currently operating tailings ponds (Figure 1). Operational and abandonment plans for these ponds follow either decant or total containment strategies. While decanting is used in 14 cases, the containment option is preferred, where possible.

## DECISION PARAMETER

The feasibility of containment depends on the water balance of the tailings pond's catchment area. In the water balance calculations, precipitation on the catchment and minewater flow are the main inputs, while evaporation from the pond and evapotranspiration from the land are the main outflows. Groundwater is assumed to be a minor factor in most areas. Based on these parameters, the design criterion to distinguish between decanting and containment is the Wetted Watershed Fraction (WWF). WWF is the pond to total catchment area ratio.

The WWF for an equilibrium state, i.e. no net change in pond level, is critically dependent on the evaporation rate. After abandonment (no mine inflows), the long term equilibrium condition is that the WWF is equal to:

$$\frac{P-ET}{E-ET}$$

where P is the annual precipitation, ET the land evapotranspiration rate and E the lake evaporation rate.

## NWT DATA

In the NWT pan data is sparse, as it is reported by only 4 AES stations and 1 private station (Figure 2). Normal precipitation and lake evaporation data for the AES stations show that lake evaporation is greater than precipitation (Figure 3). This indicates that the WWFs of natural catchments are less than the equilibrium value, since natural lakes in the region are not ephemeral.

## NEED FOR VALUES

Representative evaporation values for a greater percentage of the NWT than presently represented by the available pans are required for planning and design of tailings ponds. The evaporation values should be easily obtained and robust so that they can be agreed upon by private and public agencies. Determination of the values cannot wait until a pan data network is set up and operated for a number of years and thus must rely on available data.

It is hypothesized that an adequate set of values can be obtained using available models, the prime candidate being Morton's model. These values could then be verified by water balances at suitable confinable ponds or by comparison to available pan data. The stations collecting data required by Morton's model provide a reasonable network of values (Figure 4).

## STUDY SITES

Some designers had been using evaporation values of 745 mm for the Salmita Mine area north of Yellowknife. This originally led them to assume that abandonment could be based on total containment. A water balance of the pond was carried out by the author. Unlike most sites in the NWT, this was possible because pond elevations were available for the 1984-1986 period, no leakage from the pond was detected, no decanting had taken place and there were three precipitation stations within 200 km. It was arbitrarily assumed that the land evapotranspiration rate was half the water evaporation rate. The results are indicated in Figure 3. The 400-450mm of lake evaporation calculated was insufficient for long term containment and resulted in the formulation of a new abandonment plan. This site may continue to be useful in providing a check on any model-derived values.

Another such site is the Lupin Mine on Contwoyto Lake. Precipitation and pan data measured there in 1983 and 1984 showed evaporation to be less than precipitation (Figure 3) which seems to contradict the results at the other locations. Further studies of the tailings pond's water balance could resolve this and determine the relationship between pond and pan evaporation rates.

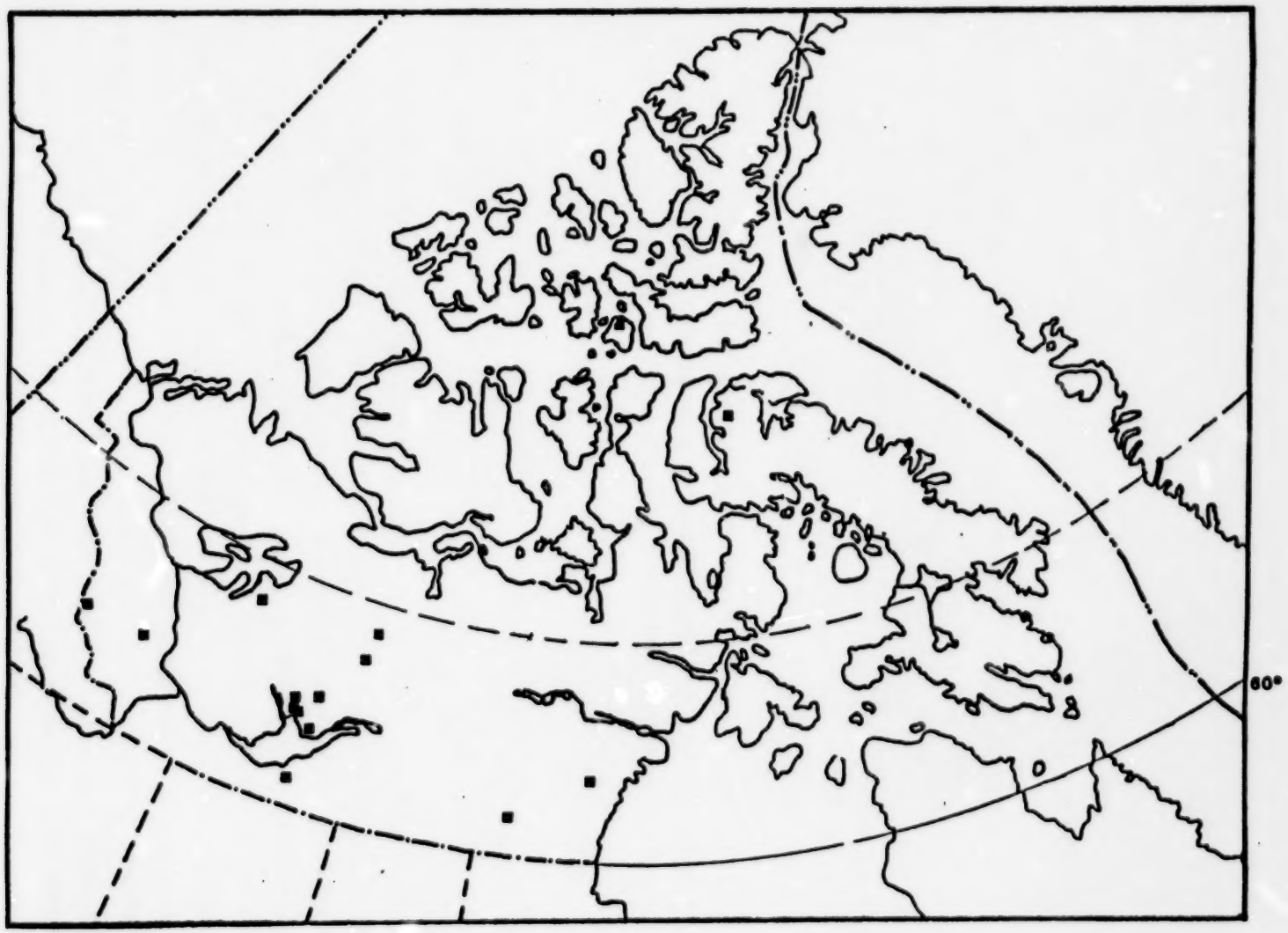
## FURTHER CONCERNS

In order to prepare preliminary evaporation values for the NWT, the following concerns need to be addressed:

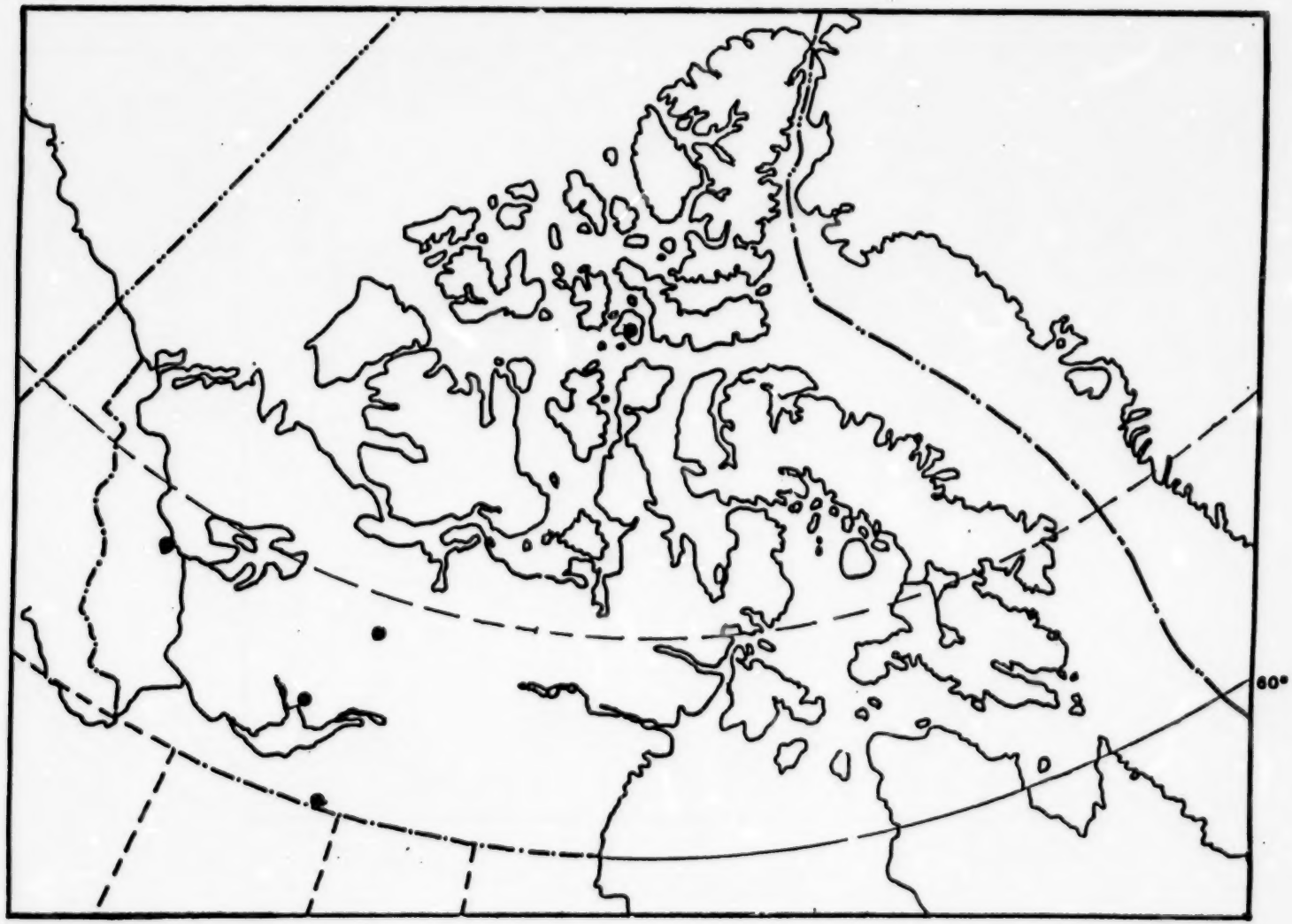
1. choice of a suitable model;
2. establishment of the minimum data required for use of the model in new locations;
3. quantification of snow undercatch, which may be as much as 50% in high latitudes;
4. extent of evaporation/sublimation from snow;
5. conversion of lake evaporation values to values for tailings ponds, and;
6. comparison of results with water balances and detailed evaporation studies.

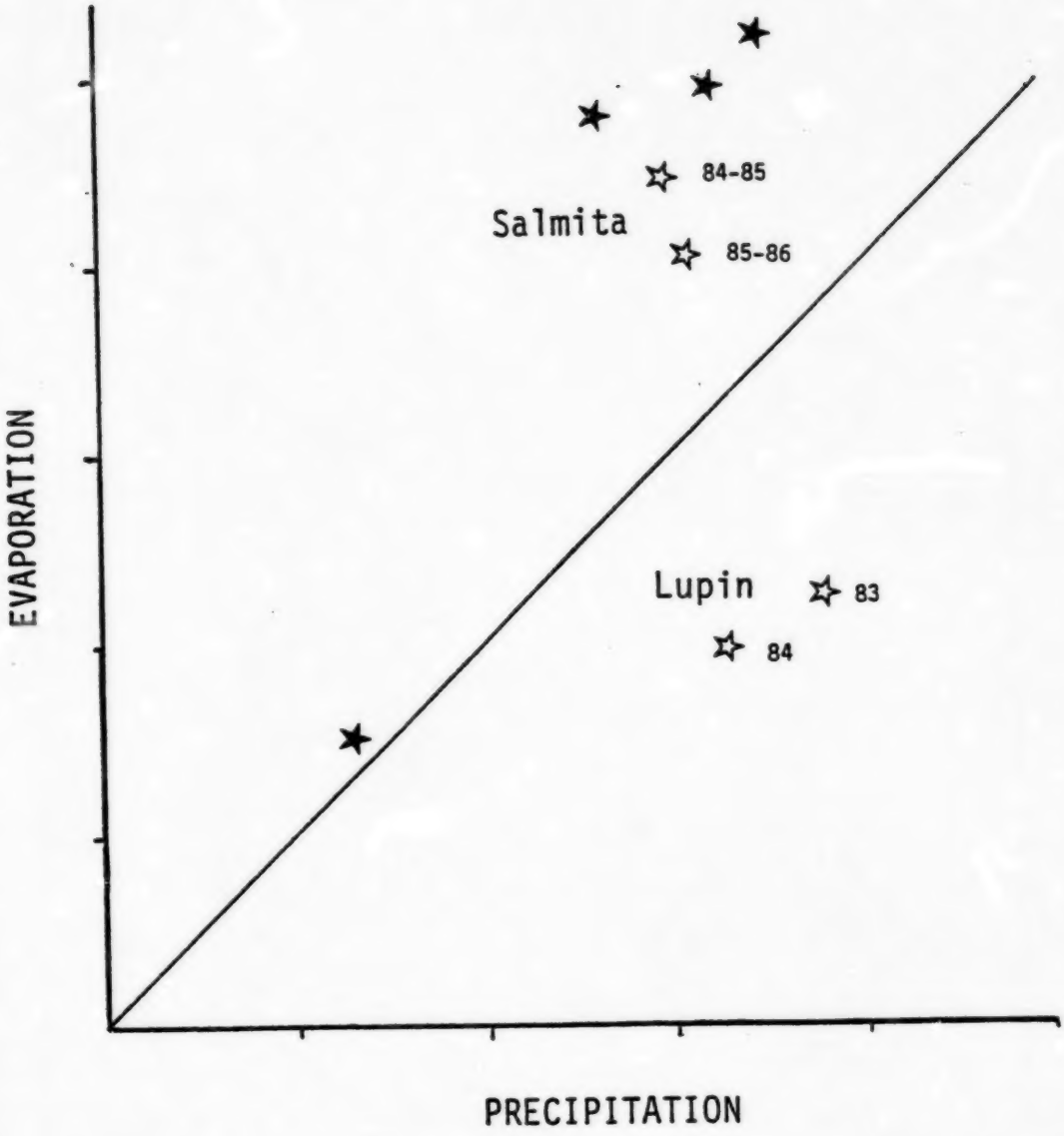
Suggestions in any of these fields would be appreciated by the author.

# Water Licences - Mines 1987

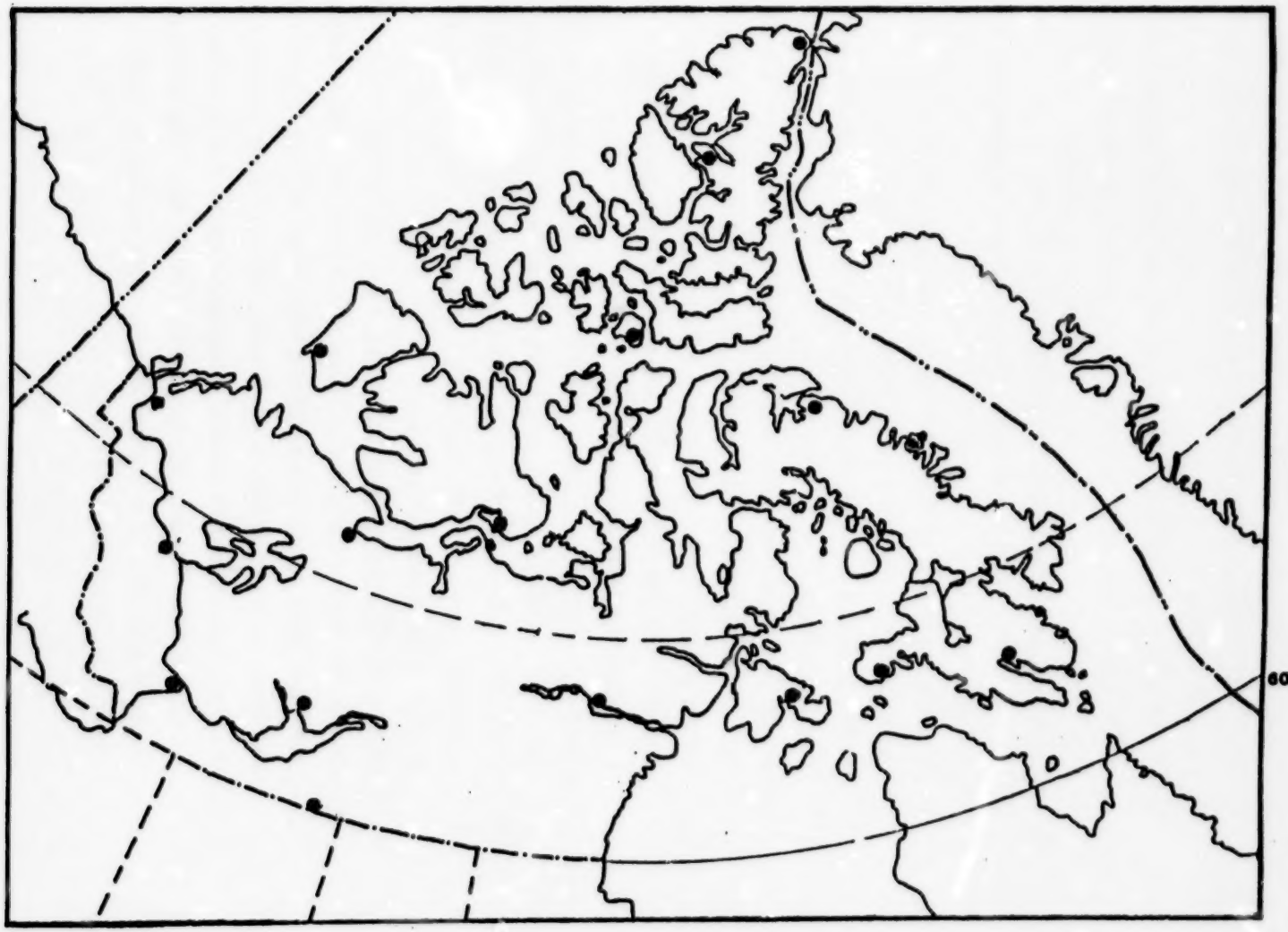


# Stations with Evaporation Pans - NWT 1987




EVAPORATION
PRECIPITATION
Salmita
84-85
85-86
Lupin
83
84

Stations Recording Sun, Temperature and Synoptics - NWT 1985



SUMMARY OF DISCUSSIONS IN SESSION V **May 21, 1987**

1. Cost-benefit: hydro power R. Divi
   Q. Was the price of electrical power used based on average cost?
   A. Yes, it is a typical cost.
   Q. Then what you are talking about is really the low end of possible cost estimates.
   A. Yes, it is.
2. Lake Diefenbaker Evaporation Ron Hopkinson
   Q. The streamflow error was quoted as larger than the evaporation error, can you comment?
   A. The estimated error of streamflow in the river is 3 to 4 percent. That is of the order of magnitude of the evaporation. If the evaporation can be estimated to 50 percent of its value, we still cannot verify it, so we cannot achieve very much by refining it.
   Comment: The streamflow error estimate (of 5%) is the error of the water meter usually used. For the comprehensive measurement program applied, the overall average error is probably less than 5 percent. Evaporation is of most concern when the flow is small, and the evaporation is an order of magnitude larger than errors in the streamflow (Yee).
   Comment: Quality hydrometric records have an error less than (plus or minus) 4 percent for each data point, which means that the error of average streamflow is much less than 4%. The evaporation is 3 or 4% all in one direction. They are small compared to streamflow, but we still want to know more about the evaporation losses.
3. Groundwater and Areal Evapotranspiration G. van der Kamp
   Comment: This sort of thing (use of groundwater head to measure water and snow load changes with season) has a huge potential benefit insofar as recent and future research in hydrology. If you really got a huge lysimeter like that working, it would answer much the research problems in hydrology. If you can keep a water balance of a large area, I would think that great progress would be possible. Of course, getting the thing working would be a major research project in itself (Morton).

Comment: I see that in measuring evaporation from lakes there is always a seepage factor. The boundary between soil moisture and groundwater is largely institutional rather than physical. We need more communication between the surficial and groundwater hydrologists (van der Kamp).

Comment: There is an ongoing water balance study in Manitoba on an 85 square mile watershed. The soil is sandy, and there is no surface runoff. The groundwater flowing out of the watershed is monitored at a stream gauging station. Estimating the water balance is proving difficult. One of the problems is considerable variations in soil moisture at a depth of 20 feet (Warkentin).

## SESSION VI: WORKING GROUPS ON MAY 21

**Chairman - R.G. Lawford, AES., Saskatoon**

WORKING GROUP I May 21, 1987

Rapporteur: A. Warkentin

The Working Group sessions and a list of participants are introduced on Page 33, with the proceedings of the session on May 20 (Editor).

Question 1. What are the principal physical processes which are inadequately represented in the more frequently used techniques for estimating i)evaporation and ii)evapotranspiration?

Response The discussion was separated between i) and ii) above.

i) Evaporation. In mass transport, there is a problem of using vapour pressure gradients measured over land, for application over water. Horizontal gradients of temperature, humidity and wind are not properly known for this application. These gradients vary considerably over time scales of one hour to one day.

When the application of the Meyer formula is viewed three-dimensionally, the variations mentioned above come into play, as well as an estimated, rather than measured wind and dew point at the standard height above ground. Similarly, water temperatures are usually estimated from few or no measurements on the lake surface. The models usually applied for these estimates are empirical rather than physical.

For the application of the Morton Complimentary Relationship Model, the radiation balance must be estimated with some model. It is possible that a better albedo model could be derived from further research. The measurements of radiation are all done at land stations, and the effect of water on cloud cover is assumed to be the same for all basins.

Some other physical process problems with this model include: a rather crude heat storage method; a lack of sensitivity to temperature and humidity. These features make the model less adaptable to the scale differences between large and small lakes.

For the Bowen Ratio technique, there may be a serious problem from the assumption that the eddy transfer co-efficient is the same for latent heat as for sensible heat.

For other models requiring energy balance estimates, there is always the difficulty that the energy balance is difficult to model in components. The main concerns are spatial variations of unknown pattern and magnitude.

ii)Evapotranspiration. There are considerable knowledge gaps in the science of hydrobotany, the interaction of soil, plant and atmosphere. There are unknowns about the response of stomata to sunshine, atmospheric conditions, and soil conditions, including moisture.

The moisture diffusion through a crop or forest canopy is not well modelled at present.

The absorption of radiation by leaves varies considerably between plant species and crop type, and thus it is not well defined for purposes of evaporation or water balance models.

Soil properties are not well enough known due to the variability of soils and their moisture conditions over an area. More importantly, the processes of soil moisture storage and conduction may not be well enough understood and characterized. The concepts of conductivity, field capacity, wilting point, saturation and infiltration may need better definition in order to serve with evapotranspiration models. The concept that AE (actual evapotranspiration) is driven in direct proportion to PE potential evapotranspiration is erroneous for many applications.

Question 2. What are the priority research problems which must be addressed in improving the estimates of evaporation on scales of i) a point; ii) a small watershed 2x2 km; iii) a global water balance sub-model (grid elements 100 x 100 km)?

Response Field sized problem. The Working Group recommended the priority on research into advection and convection processes, and turbulence with respect to field sized problems. More work is needed to define how representative point measurements and estimates of processes are with respect to field-sized areas.

It was felt by this Group that the applications on this scale are mainly for agriculture. They also noted that small-scale studies are a step toward understanding the same processes on a large areal scale.

Large scale problem. Process research needed with respect to the large scale is mainly for the loose ends of the water balance: turbulent transfer of moisture and groundwater inflow-outflow from a large basin. This will involve first, a careful review of other peoples' work to ensure that we do not waste time re-doing research. Second, we may have to run a very precise water balance on a medium-sized Canadian watershed.

For large scale areas, we must consider the use of remote sensing data, particularly from space-borne sensors. Work must be done to make quantitative connections between remote sensing data and water balance parameters.

WORKING GROUP II May 21, 1987

Rapporteur: Eric Light

Question 1. What role do turbulence and wind play in evaporation and evapotranspiration estimates and are they adequately represented in current techniques.

Response The importance of wind depends on time and space scales, and on the application of the evaporation estimate. For time periods up to one day, wind and turbulence are significant. For longer time scales such as a season, most models will give all the precision available without consideration of wind, unless the season is particularly different from normal. In the Chinook belt of southern Alberta, it may be appropriate to use models which do take wind into account. There are some models for monthly and annual evaporation which are fairly sensitive to wind, and the Meyers formula for lake evaporation is one of them.

There was some discussion about the effect of wind on the water demands of irrigation. The group did not contain any experts on irrigation water demand models, but those present assumed that wind is significant for irrigation.

Question 2. What are priority research problems which must be addressed in improving the estimates of evaporation at scales of: i)a point; ii)a small watershed 2 x 2 km; iii)the scale of a global circulation model with grid resolution of 100 x 100 km.?

Response The group did not come up with definitive answers. It was noted that models in use must be properly calibrated for the application in which they are being used. It was also noted by the N.W.T. representative, that he has a typical application for models that do not require calibration. His territory has very few observation stations, either current or historical.

WORKING GROUP III May 21, 1987

Rapporteur: James D. Rogers

Question 1. Which techniques for estimating evaporation and evapotranspiration is most appropriate for:

i) estimates on an hourly basis.

ii) estimates on a daily basis

iii) estimates on a monthly basis.

Response This Working Group split its response into the time scales above, and into two space scales which were: the point or very small and the regional, but not global, large scale. The Group noted that we have techniques to meet these needs, but we seldom have all the data necessary to calibrate them well enough to meet all needs.

| | TIME-SCALE | | |
|---|---|---|---|
| | HOUR | DAY | MONTH |
| POINT | Penman | Baier-Robertson | Meyer |
| REGION | Remote Sensing | Baier-Robertson Remote sensing | Morton (or Meyer?) |

There were a few comments to go with the matrix above. The small-scale and short-time estimate is best treated with something which takes the physics fully into account. For short time scales, measurement is best, but over large areas this means trying to use remote sensing where a technique is feasible and/or proven. It was noted that for large areas and long time scales, all the models use some assumptions and most have not really been tested completely on a large scale. The group was not sure whether Morton's or Meyer's formula was best for monthly large-scale estimates.

Question 2. What are the priority research problems which must be addressed in improving the estimates of evaporation:

i) at a point

ii) for a small watershed with a scale of 2 x 2 km.

iii) on a scale of the type commonly used in global circulation models (grid resolution 100 x 100 km)?

Response In general, the Group saw a need to find ways to operate existing models better with existing sparse data. On the small scale, the priority is on understanding and modelling the processes in the near-surface layer of the atmosphere.

On the daily time scale, for small areas, a need is seen for better, more economical data collection systems. A total cost of $1,000 per year per site was quoted as a target.

This Working Group thought that existing models are not well enough tested for a rational comparison to be made. They thought that definitive intercomparisons of models should be run on both the daily and monthly time scales. To help with the problem of using existing sparse data, the Group thought work should continue toward better estimators of lake water temperatures from the better-known air temperature.

The Group would like to see improvements in the application of remote sensing for real-time or short time scale estimates of areal evaporation. They noted a need to improve our capability to make useful observations through a cloud cover.

The Group encourages continuing work on snow loss due to evaporation, particularly in the spring. This is an area of evaporation estimation that is not yet well understood. Similarly, the Group feels that more needs to be known about how land use changes, and changes in moisture condition of land or areas of small lakes affects rates of evaporation.

DISCUSSION IN PLENARY SESSION, May 21, 1987

1. Development of Data Collection

- There is a lot of interest in improved data collection, both extension to new definitive measures for research, and application of remote sensing for areal observations.
- The AES is moving in the direction of more automated observation sites, and less sites overall.

2. Physical versus empirical methods

- Physical methods should be used for short time scales and empirical methods should be used for long time scales.

3. Research needs

- One comment was that the list of needs was lengthy, perhaps indicating not very much is known at present.
- What is needed are better ways to apply models now available. There are often errors in application of existing models, due both to lack of understanding and lack of appropriate data.
- There are a lot of qualitative judgments about what is best for a situation, choosing from a suite of models, none of which has been tested against real data.

4. Appropriate quality of estimates

- What are the appropriate criteria for selecting an estimator of evaporation?
- One criterion is to find whether the need is for a number, or a number somewhere near reality, or a precise estimate.
- One answer to that expressed by the Working Groups, is that if the number is good enough to allow us to do our job, that is good enough.
- The fortunate thing is that the end products are incontestable, and therefore they are 'good'. On the full scale of hydrology, no one has accurate enough measures of the other factors in the water balance to precisely verify the evaporation.

- People in water resource management or research have to make estimates on the basis of their personal best judgment, in order to get on with their jobs.
- From a user standpoint, obviously we have to use some value for evaporation, and we will continue to do so. A rational estimate should be made of how precise the estimate is and how much benefit there would be in a quantitative improvement of the precision of estimation. It may be possible to set a reasonable value on the research efforts to improve the estimators.

5. Testing the estimates

- It is a concern that there is no definitive measure. What is done is to take a judgment call, or a democratic vote of experts, or to average good and bad estimates together. None of these are physically sound bases for getting a best estimate.
- An appropriate small watershed or watersheds should be used to do a complete water balance and test the evaporation estimates.
- The Big Quill Lake data base from the IHD is available for further analysis.

## SESSION VII: REPORTS ON NEW INITIATIVES

### GEWEX - Global Energy and Water Cycle Experiment

by
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The Global Energy and Water Cycle Experiment is planned for the years 1995 to 2000. The objectives are to determine the global transport of water and energy in the atmosphere and the earth's surface and to predict changes in the water distribution from natural or human activities. It comes under the World Climate Research Program (WRCP) in which the concentration will be on studying global precipitation, evaporation and water vapour transport. It will parallel the Tropical Ocean and Atmospheric Interaction Study (TOGA) and the World Ocean Circulation Experiment (WOCE). The GEWEX effort is justified by the need for a better global understanding of the global fluxes of energy and water in connection with the concern for the developing greenhouse effect. It is timed to take advantage of the planned launching of a U.S. space station between 1995 and 2000. It is hoped that new computer facilities and space-borne sensors of that era will prove useful to this program.

The program is in three phases: i) before 1995, a build-up of technology for the experiment; ii) during 1995-2000, operational data gathering; and iii) overlapping these, exploitation of the technology and data to get some interim answers. The nature of the problem demands co-ordination of data from multiple sources.

The basic requirements are a model of the climate effects of the heat and water flows, and then a global observation program to provide data to calibrate and run the model. The global observation programs planned for seven basic parameters are described here.

Temperature and humidity: The program will require a three-dimensional measure of heat and water vapour on a monthly time scale with a 100 km scale. The sensors will be new infrared sensors giving better accuracy and vertical resolution than at present. Microwave sounders will also be operated from geostationary and low orbit satellites.

Winds: Global three-dimensional wind fields are required for the advection terms. Improvement is especially needed over the oceans, now a data-sparse area. Winds at the ocean surface will be mapped by passive and active microwave sensors looking at capillary wavelets. A proposed new WINDSAT will carry a LIDAR to map three-dimensional wind fields, but only in clear areas.

Radiation budget at the top of the atmosphere: We need the net energy received (incident less reflected and re-radiated) to better than 0.5% error in order to model the greenhouse effect to within 1 Kelvin. The space station will fly an improved radiation budget suite to measure solar constant, albedo and infrared radiation.

Clouds: Global cloud cover is needed in order to model the cooling and warming effects of the cloud blanket. A proposed ranging LIDAR to fly in 1995 will measure the cloud top profile. It is also expected that improved visible and infrared sounders will fly on regular weather satellites in the late 1990's.

Ground radiation budgets: The long and short-wave radiation at the earth's surface must be measured in order to land surface temperature and evaporation and surface heat mixing over the oceans. New developments are required in satellite observations to monitor cloud optical thickness and calculate the shortwave budget at the base of the clouds. Observations of down-coming long-wave radiation from the clouds will be made by surface-based sensors.

Precipitation: Rain radars will be flown on as many as three satellites to monitor precipitation in severe storms and improve satellite estimates of rainfall.

Surface heat and moisture fluxes: We need to couple the surface processes with the atmospheric processes, even when the evaporation is from a small wadi. This will be inferred with models driven by temperature and water vapour, and vegetation indices mapped from space or other sources.

Conclusions: GEWEX will help define the global hydrologic cycle and with TOGA and WOCE, it will help focus climate research in the near future. It is a research opportunity to participate in the global program of modelling the surface-atmosphere interaction, with all the technological development that entails.

# THE FIFE (First International Field Experiment) PROJECT

By
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Agrometeorology, Land Resource Research Centre
Research Branch
Agriculture Canada

The International Satellite Land Surface Climatology Project (ISLSCP) was initiated to address the research problems associated with the interpretation and exploitation of satellite data over the earth's land surface. The objectives are to develop techniques to infer climatologically important land surface parameters from satellite observations. A series of experiments will be carried out in various countries under this project during the next decade. HAPEX MOBILHY which was an Hydrological Atmospheric Pilot Experiment was the first such experiment. It was carried out in France in 1986 over a 100 km by 100 km area. FIFE, which is the first official ISLSCP experiment, will be carried out on a 15 km by 15 km area on the Kansas prairie near Manhattan, Kansas in 1987.

Twenty nine research groups funded by NASA will take part in this experiment. Most of the groups are from the USA but small groups from France, Great Britain and Canada are also participating. There will be a data acquisition program which will consist of:

a) A quasi-continuous surface flux network and weekly measurements of soil and vegetation properties.
b) An aircraft data acquisition program for spectral radiances and flux measurements of $CO_2$, heat and water vapour.
c) A satellite data acquisition program from SPOT, NOAA, LANDSAT and GOES.

Four intensive field campaigns will take place between May 26 and October 16.

The Canadian group which consists of representatives from the National Aeronautical Establishment of NRC, Canada Centre for Remote Sensing, Atmospheric Environment Service, Agriculture Canada and McGill University will be measuring $CO_2$ and $H_2O$ fluxes over the site during two of the four field campaigns using fast responding sensors mounted on the National Research Council Twin Otter aircraft in order to relate these measurements to ground based and satellite observations.

The FIFE data system will be available on a VAX 11/780. Until 1990 the data will be available only to the principal investigators but after that period it should be possible to obtain the data by contacting the main organizers: F. Hall and P. Sellers from Goddard Space Flight Center, Greenbelt, MD, 20771.

# WMO PROJECT ON THE INTERCOMPARISON OF METHODS AND MODELS FOR ESTIMATING AREAL EVAPOTRANSPIRATION (ET)

report by
P.Y.T. Louie
Canadian Climate Centre
Atmospheric Environment Service

## BACKGROUND

At the Seventh session of the WMO Commission of Hydrology (CHy) meeting held in 1984, Canada proposed a project for the intercomparison of methods and models for estimating areal evapotranspiration. The original draft for this project was prepared by Drs. Morton and Klemes of NHRI.

Based largely on the Canadian project proposal, a final draft outline for the project was prepared by Dr. A. Becker, CHy Rapporteur on Hydrologic Models and endorsed by the CHy Advisory Working Group. THe WMO Secretariat sent out to its members on August 1986 a copy of the project outline to solicit interest, comments and names of officials from member countries to be involved in further planning activities.

Canada has indicated its intentions to fully participate in this project and named as points of contact:

P.Y.T. Louie (AES, Downsview)

Dr. W. Nicholaichuk (NHRI, Saskatoon)

## PROJECT OBJECTIVES

### General

To intercompare available models (methods) which provide estimates of areal evapotranspiration for time intervals < 1 month and which require only routinely observed data and easily collected information as input.

### Specific

To catalogue and classify currently available evapotranspiration models and to compare their theoretical basis, structure, input data and computational requirements.

To select suitable test river basins for which there exists a data base which is adequate for the intercomparison and testing of evapotranspiration models.

To numerically intercompare and evaluate the models on their ability to provide areal estimates of evapotranspiration (range of validity, limits of applicability, etc.).

To prepare and disseminate the study results and provide guidance on the use of evapotranspiration models of various applications.

To contribute to a better understanding of the process of evapotranspiration as an extremely important component of the water cycle.

## SESSION VIII: WRAP-UP SESSION

### SUMMARY OF THE WORKSHOP
by John Maybank

I have put together a few observations made in the course of this Workshop, and a few indications of where we were crying out for more realistic approaches, or better measurement techniques and so forth. Basically, I think one of the interesting things about this whole thing is that we have brought together for evaporation, as one factor in the hydrologic cycle, people who are interested in it for several different reasons.

I noticed a division of interests into water management, and soil management or crop management. For each of them, the needs are different, the approach is different, and the intent is certainly different. What's happened is that, time and again people have looked at it from their own research area, which is very sensible and logical enough. But, it has also meant that many of us have had our eyes opened to some quite divergent needs for evaporation measurement and evaporation calculation or estimation. Throughout my summary, I will use the word evaporation, but every time I do, evapotranspiration applies wherever an estimate of transpiration is relevant.

One of the first things that came to mind as we proceeded was: what is measurement versus estimation? Rough measurement, presumably is something better than a guess, but not as good as a measurement and therefore in the category of estimation. We got all kinds of definitions, and all kinds of alternate, sometimes contradictory uses of 'estimate' and 'measurement'. I sometimes got the impression that it was somewhat subjective, that people were saying that "someone else's measurement is an estimate, and my own estimates are what I call measurements". What I consider we really were talking about was, observation is direct measurement, calculation is indirect measurement or derived parameter. I will stick to that in my remaining comments.

Accuracy was another area where we were very concerned for various reasons. How accurate shall a measurement be? How good is an estimate before it becomes a measurement? Basically, I think we did agree that use determines the accuracy

needed. Measurements which could be very rough estimates in some areas needed to be much more accurately measured in others. I think we homed in on this. For some purposes, we weren't happy with either a measurement or a calculation of evaporation, and in other cases we were satisfied because of the overall needs of the situation.

One thing that we have ignored at this meeting, is evaporation's counterpart, condensation, which in a great many situations is totally irrelevant, insignificant or unnecessary, and in others is an extremely important process. And it is a completely analogous one. We can ignore, and rightly do ignore dew formation in a great many water balance situations, and yet in some cases it just simply can't be ignored.

The analogy leads in some respects to one of the equations that has gained wide favour here. The basic driving force of evaporation is identical to the driving force for condensation. It is the vapour gradient between the surface on which the process is taking place, and the atmosphere at large. This force immediately comes to the fore in the Meyers equation and things like that. You have a different temperature in each case, but whether the temperature gradient is positive or negative is the key distinction between evaporation and condensation. Every formula, every equation that we work with effectively must come down to that situation of substituting for this driving force by some other route that may be more easily measured, more available or more appropriate to that particular occurrence and occasion. As an example, in the only evaporation work I've ever done, the time scale was a matter of seconds and the accuracy needed was in the fractions of microns. This was in very small droplet evaporation. Fortunately, at that stage, you've got rid of wind as a variable. The only wind speed you've got is the nice, easily measurable settling velocity of micron-size droplets. Condensation or evaporation proceed very nicely one way or the other depending on that driving force, but you wind up with the ultimate situation, where you even have to take the curvature of the surface into account. Fortunately, for Diefenbaker Lake and others, that doesn't have to be done.

In the course of the last couple of days, we seem to have been looking at calculation and observation as almost rival methods of arriving at a measurement or at the very least an estimate of evaporation. From the calculation side, we have Meyer's equation, Morton, etc., the whole series of calculation which derive from that driving force. On the observation side, we have the Class A Pan, which nobody is

very happy with, and few alternatives to it. I think, in general, the rules that I have here apply on both sides of this. "If it isn't broke don't fix it". And "don't replace something whose weaknesses and limitations you know, for something whose weaknesses and limitations are only guessed at." That applies both to the model (the calculation) and to the observing instrument.

With regard to the models, one problem keeps coming up, and we got into this several times: the input parameters. If you go to a calculation, are those things that you need to base the calculation on well observed, is the network in place, is the record there or not? You do wind up with that consideration, and we had several examples here where sometimes the calculation route was nowhere near as sensible as some sort of direct attempted observation, just because what was needed wasn't available.

I think here, we are going to have to be realistic. We are going to have to say, from now on, with respect to other meteorological parameters, why do you want them, where do you want them, and how often do you want them? And given the state of Atmospheric Environment Service financing, we are going to have to say why we want them, and why we will get a definitely better calculation of evaporation by having them.

If an equation is beautifully known, and everything is very well grounded theoretically, surely you don't need to observe any more. For example, nobody needs to observe the rate at which droplets condense in a cloud, or observe the rate at which they might evaporate in the upper reaches. The equations are well known, and the quantities that go into them. In some other cases they aren't.

We are going to need, I think, something like the Class A pan, to test some of the new calculations, instead of arriving at an opinion or conclusion by a vote or some other route. If that is the case, what sort of instrument is most sensible? Any time you try to get the Class A pan more realistic, it becomes extremely complicated, and never becomes quite realistic. I think the only realistic device for measuring, say the evaporation from Diefenbaker Lake, would be a complete Lysimeter of Diefenbaker Lake, probably on about the same size, and built parallel to it, because naturally you would want to have it in the same temperature and climate regime. But if it was downwind of it, you wouldn't have it as good as having it upwind, so

maybe you need two. And that's the ultimate idiocy of a realistic measurement observation unit.

Lysimeters? I don't think anybody has ever been really satisfied with them, except in very specialized circumstances, because the more you try to make them realistic, the more complex they become, and the complexity goes up faster than the realism is achieved. Some of the simplest devices may offer the right answer. For example this white Livingstone Sphere as you heard, is a cheap and useful device.

Whatever we need, we are going to have to automate. I think that has to be realistically recognized. It will not be because of use in isolated locations. If you like, the most isolated locations of today are city offices on a Saturday or Sunday, as an airport observation point could be, or an Agriculture Canada research station. For that reason, automation must be seriously considered.

With regard to research needs: they seemed enormous, since everybody had more research needs. We did definitely find two new research directions: the groundwater integration, and remote sensing.

It is not that continuing to look at pieces of the hydrologic cycle in isolation is all wrong, but that the very practical value of the groundwater system in other parts of the hydrologic cycle was very clear here today. I would say that this integration of groundwater research into the whole picture of evaporation studies, is really a new direction whose time has come. Remote sensing clearly is the other one.

In every case, though you might think you have got a reasonable handle on evaporation, if you are going to look at the whole overall water budget, greater accuracy may be required in evaporation. Whenever evaporation is a significant component, and improvements occur in measuring some other component in the total water balance, further accuracy is going to be required in evaporation. Even if it is a minor component, error reduction elsewhere could well result in re-introduction of evaporation.

That pretty well does it, Mr. Chairman. Frankly we may sound pessimistic at times, but I think hydrology has gone a long way as a science. Even at SRC, we very seldom resort to the divining rod any more in hydrologic research.

Thank you.

## PANEL ON RESEARCH OPPORTUNITIES

### INTRODUCTION

Each participant was asked to give a brief review of his views on priorities for research and development related to evaporation and evapotranspiration. Those reviews are presented below, with some editing for brevity and clarity.

### RAY DESJARDINS

Large-scale experiments like "FIFE" present a special opportunity to look at things in a comprehensive way. An individual looking at a small aspect of a problem can find the untreatable factors overwhelming, and actually head off in the wrong direction. In a big project there is an opportunity to look at a question from many different directions and to experiment in a comprehensive manner.

Techniques for measurement have been improving rapidly in recent years. For example, some of the outstanding instrumentation problems of the eddy correlation technique are being eliminated.

Observations of evapotranspiration should be made with theoretically sound approaches, but not necessarily very complex. Estimates can be made with simple measurements like sensible heat and net radiation, once a calibration has been performed with a fundamental flux measuring technique.

This workshop has been good in that we have come to know people in different disciplines. I hope we can help each other in the future and I would like to encourage people to cooperate with me in joint projects.

### PAUL LOUIE

I think we must continue research into the basic processes. I do not think we have a full understanding of the basic plant-soil interactions. If we are going to get into the problems of land-use and climate variability, we will have to understand the issues. We have to have faith in our knowledge of these areas.

On the operational side, there is a basic satisfaction with the answers we are getting. However, there is a lot of misuse of some of the available data.

Available models often require data that are not available. I think there is a need to start looking at how we can estimate these basic input parameters from existing data. This will enable us to run the models (with realistic values) rather than plugging in any value and finding the model results are unrealistic.

We should look more into uses for remote sensing data in our work on water resources. We must define our needs well, in order to help with the work of developing applications for remote sensing in support of evaporation measurement.

ALF WARKENTIN

At present, a different technique is used for lake evaporation in each of the three prairie provinces, at least in part because there is a lack of confidence in any one method. It seems that we should try to resolve that and stick to one method for the climatically similar Prairies. We should evaluate the different methods, comparing hourly, daily and monthly with some absolute measure of evaporation. If none of the present estimators is reasonable, then we should go back to basic processes.

The WMO Intercomparison study is a good starting point for evapotranspiration. If work is needed on new models, we should still try to circumvent re-studying soil-plant-atmosphere interactions. These are too complex and expensive to study properly. We should, for example examine Morton's and similar models. As with evaporation, some absolute measure of evapotranspiration is needed in order to calibrate the various models.

Point of clarification: I would like to say that the Complimentary Relationship doesn't state everything. A proper understanding of soil-plant-atmosphere relations is essential if we are going to be predicting the effects of land-use changes (Fred Morton).

VIT KLEMES

Whether we want it or not, we do need to proceed from crude empirical relations to some which are better grounded in science. There are continuing problems which require a more fundamental understanding of process.

There is no conflict between a lack of knowledge and the necessity to make decisions. You cannot wait for the perfect diagnosis before making a decision to get on with things.

For those of us involved in applications, we must first consider what is the final problem. In applications, the final problem is not evapotranspiration, it is crop yield or hydro power production. The direction of research should be to solve that final problem.

DON GRAY (Invited Comment)

I think we may be neglecting verification of models. We need to test existing models at several levels. I see very few presentations on sensitivity analysis. We have done some studies on the Prairies using an energy balance approach. We found that if net radiation is changed by, say 5 percent, then it will give an equivalent change in all the other terms in the energy balance. So net radiation is the dominant flux. If you get a handle on the net radiation, you don't need to worry about those other terms, except in special cases.

The ultimate plea I would make, is the lack which I see in hydrology today, of some quality measurements on which to test some of these hypotheses. Very few people are going out in the world these days and making any measurements. I don't see how on earth we can hope to meet some of our objectives without making some attempt in this direction.

## PLENARY SESSION DISCUSSION ON RESEARCH PRIORITIES

### 1. Models, Land and Water

Comment that the modelling approaches in use imply that the processes of evaporation over land and water are not related. This commentator would like to see a common set of equations for land and water processes run on a common data set. He sees that if a model is run on ten years of data and a bias appears, then this can be corrected out. If, on the other hand further information completes the water balance, the bias term in the model may show the effect of land use change or other effects.

### 2. Remote Sensing

It is not believed that remote sensing will help hydrology research very much. Radar remote sensing has been little use in hydrology research, and no quantitative results have ever been produced from satellite remote sensing .

There was a comment that radar has been around for forty years, for storm tracking, and over the years, radar engineers have diverged in interests from hydrologists, with less and less communication between disciplines. Radar engineers have been busy tuning the system, while hydrologists wanted answers that were not yet available from this tool.

### 3. Model philosophy

One cannot deny the necessity to have benchmark data against which to test under the widest variety of conditions. We can, however make models to fit any data set. The more important thing is to concentrate on models that have the potential of achieving the ideal of not needing local calibration. This is especially needed for prediction of land use change where future model calibration data would simply not be available.

There was further discussion on the application of models, and appropriate aims of precision of estimates. For ordinary streamflow forecasting, an error of +/- 20% is quite acceptable. That precision is available with present models. Research is needed to improve on that, but the effort should be directed toward some end goal other than simply improving estimates of evapotranspiration. That goal is likely to be an escape from empiricism in order to better predict the future effects of major water developments or land use changes.